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Immediate memory for pseudowords and phonological awareness are associated in adults and pre-reading children

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Abstract
This study investigated phonological components of reading skill at two ages, using a novel pseudoword repetition task for assessing phonological memory (PM). Pseudowords were designed to incorporate control over segmental, prosodic and lexical features. In Experiment 1, the materials were administered to 3- and 4-year-old children together with a standardized test of phonological awareness (PA). PA and pseudoword repetition showed a moderate positive correlation, independent of age. Experiment 2, which targeted young adults, employed the same pseudoword materials, with a different administration protocol, together with standardized indices of PA, other memory measures and decoding skill. The results showed moderate to strong positive correlations among our novel pseudoword repetition task, measures of PM and PA and decoding. Together, the findings demonstrate the feasibility of assessing PM with the same carefully controlled materials at widely spaced points in age, adding to present resources for assessing PM and better enabling future studies to map the development of relationships among phonological capabilities in both typically developing children and those with language-related impairments.

Keywords: *phonological memory*, *phonological awareness*, *pseudoword repetition*, *decoding*, *assessment*, *preschool children*, *young adults*

An essential component of successful reading is the ability to *decode* – to identify the phonological form of a word from its encipherment in print. Decoding skill is predicated on a grasp of the alphabetic principle: in alphabetic orthographies, letters generally represent phonemes. In order to assimilate this fact, the beginning reader must develop knowledge of letters, awareness of phonemes as units of speech and knowledge of the mappings between letters and phonemes (Liberman, Shankweiler, & Liberman, 1989). Phonological awareness (PA) is the ability to parse the phonological structure of familiar words into their various constituents, syllables, onsets and rimes, phonemes, and to consciously manipulate one or more of those units (Liberman, Shankweiler, Fischer, & Carter, 1974; Mattingly, 1972). Phoneme awareness is a more specific ability, narrowly focussed on attending to or manipulating the individual phonemes within words or syllables, the aspect of PA most obviously relevant for alphabetic reading (Scarborough & Brady, 2002). A necessary resource for success in

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these tasks is phonological memory (PM). This is a putatively domain-specific temporary storage system, arguably a part of the human specialization for language, which is geared toward retention of the products of speech production and perception (e.g. Baddeley, 1992; Crain, Shankweiler, Macaruso, & Bar-Shalom, 1990). As a short-term workspace, it provides for retention of a word's phonological representation while its syntactic and semantic features are retrieved from the lexicon.

This study describes a new pseudoword repetition task designed to assess phonological immediate memory. Pronounceable pseudowords are the appropriate stimulus materials for this purpose because they are exclusively phonetic structures that resemble words phonotactically but are lacking in meaning or other aspects of language form. Our pseudoword test is newly designed for use both with young, pre-reading children and older readers at varying stages of skill acquisition. To this end, it incorporates careful control over the determinants of wordlikeness (e.g. Dollaghan & Campbell, 1998; Gathercole, 1995; Graf-Estes, Evans, & Else-Quest, 2007), as well as incorporating a rhyme–non-rhyme contrast (e.g. Mark, Shankweiler, Liberman, & Fowler, 1977). These features enable the valid assessment of PM uncontaminated by non-phonological information that is inextricably associated with actual words. In one experiment, preschool children are given this task in combination with a well-documented, standardized assessment of PA, the PA subtest from the Test of Preschool Early Literacy (ToPEL; Lonigan, Wagner, & Torgesen, 2007), in order to provide preliminary validation of the novel PM measure. A second experiment deploys a cognate pseudoword task among young adults with a wide range of literacy skills. There, we use the same set of pseudoword materials to evaluate relationships between performance on this experimental memory measure and a standardized measure of phonological (primarily phonemic) awareness, the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999), as well as measures of verbal and visual memory, and decoding skill.

Thus, the purpose of the study is to investigate relationships between PM and PA in pre-literate children and a sample of young adults selected for wide variation in reading skills. A secondary purpose was to probe for a rhyme interference effect on recall in age groups outside those in which it has been previously demonstrated. The first experiment, with preschool children, serves to establish preliminary validity of a verbal memory measure that can be administered with low attrition to preschool children, providing a necessary tool for subsequent studies aimed at mapping developmental relationships between verbal memory and the emergence of decoding ability and other reading-related phonological capabilities. Pseudoword materials intended for memory assessment across the developmental continuum, with careful control of important dimensions of word likeness, have been newly created for use in the present study. These materials will facilitate future investigation of how the relations between PM, other phonological abilities and reading may change with increases in reading skill and cognitive development (cf. Conrad, 1971). Data from the older group serve to evaluate the same pseudoword materials at a later point in development, and provide evidence of validity against a much larger set of literacy-related measures than can be collected from the preschool children.

In the remainder of this introductory section, we first present a brief overview of findings regarding phonological language skills in the context of typical literacy acquisition. Second, we examine these capacities in a clinical context, exploring relationships among them in young readers with dyslexia and with specific language impairment (SLI). Finally, we summarize four important characteristics of our new pseudoword materials.

PM, PA and reading in typical development

A large body of research indicates that phonologically grounded capacities are integral to reading achievement (see reviews by Lonigan, Schatschneider, & Westberg, 2008; Scarborough, 2005). In particular, PM and PA have been proposed to have unique roles in typical reading development.

In a survey of longitudinal studies, Scarborough (1998, 2005) found the average correlation between memory for phonological material, as assessed in kindergarten, and later reading achievement to be 0.33, and the average correlation between PA, as assessed in kindergarten, and later reading achievement to be 0.46. In another survey, Lonigan et al. (2008) found the correlation between PM, measured in preschool, and later reading comprehension to be 0.51, and that for the relationship between preschool PA and later reading comprehension to be 0.36.

Three studies of particular relevance to the present research address the issue of whether PA and PM make *distinct* contributions to early reading achievement. In a longitudinal study, Mann and Liberman (1984) found that both PA and PM measured in kindergarten predicted reading success in first grade. In a longitudinal study of beginning readers, De Jong and Van Der Leij (1999) showed that PM, rapid serial naming and PA each had unique influences on reading achievement from kindergarten through second grade. Hansen and Bowey (1994), in a cross-sectional study of second-grade students, report that PA and verbal working memory each predict unique variance in reading skill. Collectively, these findings suggest that PA and PM may have independent relationships with reading achievement.

Moreover, as Scarborough (2005) notes, early grade-school reading achievement is predicted as well, and in some cases better, by measures of phonologically grounded capacities collected at 3 and 4 years of age than by the same measures taken at age 5. While this finding does not definitively establish the causal role of these capacities in the course of development of reading skills, it does suggest that an assessment of PM targeted for 3- and 4-year-olds will be a useful contribution to the study of the development of reading-related cognitive skills.

PM, PA and reading in atypical development

Beyond its association with reading skill in typically developing children, PM deficits are also a feature of several developmental language disorders, including dyslexia (e.g. Gallagher, Frith, & Snowling, 2000; Snowling, Muter, & Carrol, 2007; Torppa et al., 2007; see also Scarborough, 2005, for a review) and SLI (e.g. Archibald & Gathercole, 2010; Dollaghan & Campbell, 1998; see also Coady & Evans, 2008; Gathercole, 2006; for reviews).

Gallagher et al. (2000) and Snowling et al. (2007) report on a long-term longitudinal study of reading and related capacities for English-speaking children with and without familial risk of dyslexia. Children in this study were observed four times between ages 3 and 13 years. Taken together, these two studies provide substantial evidence associating reading difficulties with weaker PM skills: children with dyslexia scored significantly lower at each observation on measures of PM (including digit span and non-word/pseudoword repetition) than both non-dyslexic children with a familial risk of dyslexia and non-dyslexic children without such familial risk. Further, a composite measure of PM and articulatory-motor fluency at age 3 significantly predicted reading outcomes at age 6, more so than did an expressive language composite score, comprising measures of sentence length and vocabulary. In another longitudinal study of risk factors for dyslexia, Torppa et al. (2007) tracked a large sample of school children, both with and without genetic risk of dyslexia, from 1 to 8 years old. They found that below-average readers were characterized by significantly worse performance on PM, PA, letter knowledge and rapid naming tasks than their peers, from as early as 3.5 years of age.

As summarized by Gathercole (2006), children with SLI characteristically have markedly worse recall of pseudowords than typically developing children, especially for multisyllabic targets. Dollaghan and Campbell (1998) demonstrated that children with SLI performed at a significantly lower level on pseudoword repetition tasks than typically developing children, and that pseudoword repetition scores could be used to distinguish between typically developing children and those with SLI with a high degree of accuracy, far better than other language assessments. Archibald and Gathercole (2010) investigated a variety of linguistic and cognitive capacities in 7- to 11-year-olds with SLI, and found that while their performance on most measures was 1–1.5 SD below the normative mean, their tests of phonological short-term memory (such as pseudoword repetition) and tests of phonological working memory (such as sentence span) were far below the normative sample mean, with 95% of their participants scoring more than 1.5 SD below the normative mean for both non-word repetition and sentence span tasks.

These findings from examinations of dyslexia and SLI underscore the importance of adequate PM assessment for young children, both as a research instrument to explore the relationships among phonological capacities and language and literacy skills, and as a potential diagnostic tool for use in clinical settings. Its potential clinical utility will depend upon further elucidation of the developmental trajectory of the relationship between PM, reading and language, especially in populations with dyslexia and other developmental language disorders.

Pseudoword repetition as an index of PM

The research discussed above demonstrates that pseudoword repetition tasks have both theoretical and practical diagnostic value for assessment of PM in the context of problems with literacy acquisition and other language-related difficulties. Given that different aspects of this task may prove difficult depending on the type and severity of an individual's diagnosis, it is important that pseudoword materials not vary in uncontrolled ways. (See Coady & Evans, 2008, for a discussion of the different aspects and component skills of pseudoword repetition, especially as relevant to SLI.) Accordingly, the materials for this study were designed to control for four important phonetic and linguistic characteristics. First, prosody is controlled. The trochaic stress pattern (strong–weak; as in 'motive' /ˈmo.tɪv /) is by far the most common pattern for English polysyllabic words (Cutler & Carter, 1987) and is less subject to error than other stress patterns, so all of our materials have a trochaic meter. Second, increasing phonetic similarity of pseudoword items has long been known to lead to decrements in recall (Baddeley, 1966; Conrad, 1971). Moreover, children with good word reading skills have been shown to be less able to recall rhyming than non-rhyming pseudowords, whether spoken or printed, whereas their less skilled counterparts were not differentially affected by rhyme characteristics (Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). We manipulate the phonetic similarity of items by including equal numbers of items with rhyming and non-rhyming strong syllables. This will allow further investigation of differential susceptibility to similarity-based interference effects on recall in clinical populations. Third, recall of test items is also known to be influenced by the wordlikeness of the items (e.g. Dollaghan & Campbell, 1998; Graf-Estes et al., 2007; Treiman, Goswami, & Bruck, 1990). We controlled for wordlikeness across rhyme conditions by matching the similarity of our target syllables to actual English words using metrics provided in the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002; http://www.maccs.mq.edu.au/~nwdb/). Finally, we controlled the perceptual salience and articulatory difficulty of the pseudowords by restricting syllable complexity and presence of late-acquired phonemes. Full detail on these points is presented in Methods of Experiment 1.

Overview of current project

The primary aim of this experiment was to establish the construct validity of our pseudoword memory task by determining its associations with measures that have proved central to the development of skill in reading, decoding skill, other measures of memory and phoneme awareness. Thus, this project had two specific goals. First, we created new pseudoword materials, which are explicitly controlled in dimensions that may affect performance and were expected to be important for valid assessment across a range of ages and reading levels, and a test protocol appropriate for each of the targeted age groups. Second, we carried out experiments with these materials in order to determine their suitability for investigating parameters of reading acquisition. In Experiment 1, we probe the relationship between performance on the new pseudoword task and a standard measure of PA from the ToPEL (Lonigan et al., 2007), known to tap an ability essential to printed word recognition, in 3- to 4-year-old children. Our intent was to investigate the relationship between these key variables in pre-literate children. To this end, we also examined the differences between participants' performance on rhyming and non-rhyming items. The purpose of Experiment 2 was to establish the value of our pseudoword memory test in explaining reading differences in a sample of young adult readers representing a wide range of skill levels. We used the same pseudoword materials with a different delivery protocol, suited to adult readers. Along with the pseudoword repetition task, the young adult group received the CTOPP (Wagner et al., 1999) as an index of PA. The PA subtests of the ToPEL and CTOPP are similarly structured although each is targeted to a different portion of the developmental spectrum. The similarity in content and the fact that each is a well-documented standardized index make them appropriate comparison measures for our experimental pseudoword repetition tasks. In addition to CTOPP, the young adult participants were also given other measures with established relevance in reading research, including assessments of verbal and non-verbal memory, decoding skill and IQ.

Experiment 1: Association of PM and PA in pre-literate children

Experiment 1 investigated the relationship between pseudoword repetition scores and PA, the latter assessed with the PA subtest of the ToPEL (Lonigan et al., 2007) in pre-reading children, and probed for a difference in the recall of rhyming and non-rhyming items.

Participants

Thirty-three typically developing preschool children were recruited from Connecticut birth records provided by the state Department of Health (mean age = 45.57 months, SD = 5.65, min = 37, max = 57; 17 boys). Participants' parents completed the Haskins Laboratories Health History and Background Questionnaire, which included questions about individual health history (e.g. ear infections), hearing impairments, language development milestones and family history of learning or language problems. Participants had no individual or family history of neurological, learning, language or speech disorders, and no known hearing impairment or history of ear infections. All were from homes in which English was the primary language. Participants' parents were briefed on the protocol and gave written consent for their children to participate. All protocols were approved by the Yale University human investigation committee. Five children refused to engage with the pseudoword repetition task (two boys). Data from 28 children are analyzed below. All children received a picture book as a reward for participating in the study.

Method

Preschool participants were given two tasks: the PA subtest of ToPEL, and an experimental pseudoword repetition task.

Phonological awareness: The ToPEL PA subtest was administered first, using a procedure that was standard except in one regard. In addition to the tester, a confederate is present, playing the role of *Glerk, the Space Chicken* (manipulating a stuffed toy). Glerk cheers on the participant whenever a response is made, whether or not it is correct. This encouragement is the only way in which ToPEL administration differs from the standard administration procedure (Lonigan, Wagner, Torgesen & Rashotte, 2007). Responses on the ToPEL PA assessment can be divided into four categories defined by two dimensions: TASK (elision versus blending) and RESPONSE-TYPE (verbal versus pointing). Scores for each of the four components were tallied separately. Composite and standard scores were also computed in the conventional way.

The ToPEL PA assessment was administered first because it begins with items that require only a non-verbal pointing response, which is helpful in encouraging shy children to engage with the task. As Glerk cheers for the participant during ToPEL administration, he builds a rapport with the participant, which later helps the pseudoword repetition protocol to proceed smoothly.

Pseudoword repetition: As noted, materials for the pseudoword repetition task have four important properties. See Table I for example stimuli.

First, pseudowords for this task are composed of trochaic feet (strong–weak syllable combinations). Thus, items are consistent with the metrical properties of English. Roy and Chiat (2004) demonstrated that preschool-aged children make more errors when repeating unstressed than stressed syllables, and that unstressed syllables were even more error-prone when they appeared in an iambic rather than trochaic stress pattern, so the prosodic pattern of our materials should help to maximize successful repetition by our participants. Strong syllables were selected to satisfy specific constraints on segmental make-up, neighborhood size and neighborhood frequency, described in more detail below (e.g. /tev/). In order to form constituent trochaic feet, each strong syllable was paired with a weak CV syllable. The weak syllable always contains a schwa vowel, and its onset consonant is phonotactically consistent with the coda consonant of the strong syllable, such that the transition from coda consonant to onset consonant is well-attested in English.

Second, two classes of pseudowords (rhyming and non-rhyming) were constructed by concatenating sequences of trochaic feet. Rhyming items are composed of trochees which differ only in the onset of the strong syllable (e.g. /ˈbog.zəˈhog.zə/), while non-rhyming items have strong syllables from different rhyme families (e.g. /ˈmoɪt.səˈtev.də/). Test materials include items of both types starting at a length of two trochaic feet and increasing to length six. Table I shows three items of each rhyme condition, at length two. The full set of pseudoword materials can be found in the Appendix.

Third, because pseudoword recall is influenced by the wordlikeness of test items (e.g. Dollaghan & Campbell, 1998; Gathercole 1995; Graf-Estes et al., 2007; Thompson, Richardson, & Goswami, 2005; Treiman et al., 1990), strong syllables of pseudowords were matched for wordlikeness across rhyme conditions by matching neighborhood size (number of actual English words differing from the strong syllable by only one phoneme) and summed neighborhood frequency (total frequency of those neighboring words) based on estimates from the ARC non-word database (http://www.maccs.mq.edu.au/~nwdb/). This online database provides access to more than 350 000 monosyllabic pseudowords categorized by phonological neighborhood size, summed neighborhood frequency and

Table I. Two-trochee pseudowords and neighborhood statistics for strong syllables.

Rhyming items				Non-rhyming items			
Trochees		Neighborhood size	Neighborhood frequency	Trochees		Neighborhood size	Neighborhood frequency
bog	zə	16	1157	moɪt	sə	14	1222
hog	zə	14	1747	tev	də	15	1773
paɪf	pə	15	937	wig	zə	15	812
daɪf	pə	17	1018	fum	zə	17	980
tiv	bə	17	646	boʧ	tə	17	685
kiv	bə	18	802	dep	sə	18	874

Note: Pseudowords are rendered in IPA. Trochees are stressed on their initial syllable. Blank lines separate items; /ˈbog.zəˈhog.zə/ is a single two-trochee item.

other useful criteria (Rastle et al., 2002). For the strong syllables of all items included in our pseudoword materials, neighborhood size was constrained to fall between 5 and 20, while summed neighborhood frequencies ranged from 50 to 2000. Table I shows neighborhood statistics for strong syllables of the two trochee items. Item-wise summaries for all pseudowords are included in the Appendix. Neighborhood size (NSize) and neighborhood frequency (Nfreq) are very similar for rhyming (NSize mean = 15.6, SD = 2.2; NFreq mean = 861.0, SD = 480.0) and non-rhyming (NSize mean = 15.4, SD = 2.4; NFreq mean = 860.0, SD = 476.6) item sets. Differences between rhyming and non-rhyming items are not significant (all ts < 1.00, all ps > 0.500).

Finally, because these materials are intended for use with preschool children, the perceptual salience and articulatory difficulty of the pseudowords were given special consideration. In the first instance, all strong syllables contained tense vowels or diphthongs including tense vowels. In the second, strong syllables of pseudowords shorter than four trochees never included consonant clusters. Further, because some phonemes are typically mastered later than others, we excluded those phonemes identified by Shriberg (1993) as the Late Eight consonants (i.e. /θ/, /ð/, /s/, /z/, /ʃ/, /ʒ/, /l/, /ɹ/) from strong syllables of items of three or fewer trochees. Note that the same pseudoword materials are used in Experiments 1 and 2, although the task administration procedure differed between the two.

In Experiment 1, presentation and elicitation of pseudowords proceeded as follows. As during the ToPEL PA task, the confederate continues to act as Glerk's puppeteer and voice. Glerk is described as a recent arrival from a faraway planet who is seeking to make some friends on Earth. Glerk does not speak English, so the experimenter serves as translator to help Glerk teach the participant some words from his language. The experimenter introduces the pseudoword, then Glerk's puppeteer repeats it and finally the experimenter asks the participant to repeat the pseudoword. Thus, the participant hears each item three times before making a response. Participants' responses are judged correct if the onset consonant of each stressed syllable is produced correctly. Given that preschoolers are more error prone on unstressed than stressed syllables (Chiat & Roy, 2007; Roy & Chiat, 2004), participants' productions of unstressed syllables of the trochaic feet are not scored to avoid floor effects. A condition (rhyme or non-rhyme) is discontinued after two consecutive failures in that condition. Testing in the alternate condition continues until the same criterion is met. Scores were tallied for number of rhyming items correct, number of non-rhyming items correct and total number of correct responses.

Results and discussion

Summary statistics for the preschool PA and pseudoword repetition data are provided in Table II. Performance of our unselected sample of typically developing children on the ToPEL PA task is consistent with the normative sample (mean standard score = 105.9). Summary statistics for pseudoword repetition total number correct (mean = 6.36, SD = 2.20; min = 3; max = 11) indicate an absence of floor or ceiling effects, demonstrating that the task is well within the capabilities of our typically developing participants.

To investigate the potential presence of an interference pattern similar to that found in primary school children as documented by Mark et al. (1977), Shankweiler et al. (1979), Olson, Davidson, Kliegl, and Davies (1984) and Siegel and Linder (1984), we performed a paired t-test on rhyming and non-rhyming items. The difference was not statistically reliable ($p = 0.37$), leading us to consider that patterns of rhyme interference documented in previous studies may not extend downward into this younger population (cf. Conrad, 1971). This is further confirmed by the absence of reliable correlations between any PA indicator and rhyme–non-rhyme difference scores, as shown in Table III.

Table II. Summary of child data ($N = 28$, 15 boys).

	Mean	SD	*N*	Max. Poss.
Age (months)	45.86	6.02	28	–
Pseudoword repetition				
Raw score total	6.36	2.20	28	30
Rhyme items	3.04	1.45	28	15
Non-rhyme items	3.32	1.31	28	15
ToPEL Phon. awareness				
Standard score	105.89	11.76	28	–
Raw score total	15.46	4.20	28	27
Blending items	9.41	2.64	27	12
Elision items	6.52	2.28	25	15
Pointing responses	10.11	1.69	28	12
Verbal responses	5.56	3.18	27	15

Note: Failures to respond on any component of the ToPEL were coded as missing values.

Table III shows correlations and attendant *p* values for the relationships between component and total scores on the pseudoword repetition task and the PA task. Values in the shaded area show correlations between pseudoword repetition and ToPEL PA components. As can be seen, age is correlated with overall PA scores ('ToPEL PA: raw score total' and 'Age', $r = 0.37$), but not with pseudoword repetition ('Pword rep: raw score total' and 'Age', $r = 0.14$). Moreover, the ToPEL PA total score and the pseudoword repetition total score are correlated ('ToPEL PA: raw score total' and 'Pword rep: raw score total', $r = 0.49$). In order to determine whether the correlation between the two tasks is mediated by age, we examined the pattern of correlations after regressing age from each measure. The pattern overall remained essentially unchanged, indicating a stable relationship between PM and PA within the sampled age range.

Table III Correlations among pseudoword repetition and PA scores.

	1	2	3	4	5	6	7	8	9	10	11
1. Age	–										
2. Pword rep: rhyme items	0.19	–									
3. Pword rep: nonrhyme items	0.03	0.27	–								
4. Pword rep: raw score total	0.14	0.82***	0.77***	–							
5. Pword rep: rhyme-nonrhyme	0.14	0.66**	−0.55**	0.11	–						
6. ToPEL PA: raw score total	0.37*	0.43*	0.34*	0.49**	0.11	–					
7. ToPEL PA: standard score	−0.12	0.40*	0.32*	0.45*	0.09	0.85***	–				
8. ToPEL PA: blending items	0.39*	0.27	0.34	0.38*	−0.04	0.83***	0.63**	–			
9. ToPEL PA: elision items	0.14	0.38	0.19	0.37	0.18	0.77***	0.71**	0.28	–		
10. ToPEL PA: pointing responses	0.26	0.23	0.17	0.25	0.06	0.68**	0.57**	0.38	0.63**	–	
11. ToPEL PA: verbal responses	0.33	0.42*	0.35*	0.48*	0.09	0.92***	0.77***	0.82***	0.64**	0.25	–

Note: Grey region highlights correlations of pseudoword-repetition-derived scores with other measures.
$^{*}p < 0.05$.
$^{**}p < 0.01$.
$^{***}p < 0.001$.

We further explored the relationship between PA and pseudoword repetition using multiple regression. We targeted the ToPEL PA raw score with age and the pseudoword repetition score as predictor variables. Multiple R^2 for the model indicates the two predictors capture about 34% of variance in PA ($\beta_{\mathrm{Age}} = 0.348$, $p = 0.042$; $\beta_{\mathrm{Pwordrep}} = 0.450$, $p = 0.010$). Pseudoword repetition accounted for 20.2% of unique variance in PA, while age accounts for about half as much unique variance (12.1%); very little variance is shared between age and our memory assessment.

These results seemed to show that the pseudoword materials and repetition task yield a promising index of PM for assessing 3- to 4-year-old preschool children. An auspicious feature of the task is the distributional properties of scores, which show neither floor nor ceiling effects, suggesting that the same materials may be usable with even younger children. Finally, the relationship we find between performance on our experimental pseudoword repetition task and an established measure of PA evidences its basic validity as a precursor to literacy skills. Future work incorporating this task will look for the appearance of phonological interference effects as literacy skills emerge.

Experiment 2: Phonologically grounded capacities in young adults

Experiment 2 incorporates the same pseudoword materials used in Experiment 1, but with a delivery protocol suited to adults. The experiment investigated relationships between the experimental pseudoword repetition measure of verbal memory and other measures of verbal and visuo-spatial memory, PA and intelligence in adults with wide-ranging literacy skills. The chief aim of this experiment was to assess the relationship between scores on the experimental pseudoword repetition task and PA in young adults and to provide evidence of construct validity of our pseudoword task by investigating its relations with other measures of verbal memory, PA and decoding skill.

Participants

A community-based sample of 50 young adults (23 female), age 16–24 years, were the participants. Some, but not all, were enrolled in adult education programs, or community college. This participant group constitutes a subset of individuals recruited for a larger study of non-university young adults in which poor readers are oversampled by design (cf. Braze, Tabor, Shankweiler, & Mencl, 2007). Thus, we intend to induct a sample of individuals whose language-related skills are continuous with the general population but weighted toward the lower tail of the distribution. Participants (or their parents, when participants were under 18 years old) provided informed consent. All protocols were approved by the Yale University human investigation committee. Participants were paid for completing the tasks discussed here, as well as others not included in this report.

Method

In addition to the experimental pseudoword repetition task, established measures of verbal and visuo-spatial memory, PA, decoding skill and IQ were collected.

Verbal memory (pseudoword repetition): The same pseudoword materials are used here as in Experiment 1. See the methods of Experiment 1 and the Appendix for details. Here, however, we use a delivery mode that is more appropriate to the age of these young adult participants. Pseudowords were digitally recorded in a female voice. The participant listens to each item through headphones (once, in contrast to the three repetitions for preschool children), and then attempts to recall it to the experimenter. As in Experiment 1, pseudoword presentation alternates between rhyming and non-rhyming items, starting with items with a length of 2 trochees. The task has the same correctness and failure-cutoff criteria as described in Experiment 1. Participant's responses are judged correct if and only if the onset of the stressed syllable of every trochaic foot is recalled correctly. After two consecutive recall failures in a rhyme condition (rhyme or non-rhyme), that condition is no longer presented. The task ends when the participant reaches the cut-off criterion for both rhyming and non-rhyming conditions.

Verbal memory (sentence span): A sentence span measure of verbal working memory is modeled after the listening span task of Daneman and Carpenter (1980). Our version of this measure shares its architecture with the aforementioned task, but uses different sentence materials. These new sentence span materials have several advantages over those of Daneman and Carpenter. Sentences were designed to have truth values that would be easily accessible to a non-college-educated population. The new materials are more similar (to each other) in length, ranging from 9 to 11 words and 15 to 17 syllables. Materials consist of declarative sentences and contain no relative clauses. Target words are always nouns or adjectives. There is no repetition of target words, and minimal repetition of other vocabulary.

Participants listen to short lists of pre-recorded sentences. After each sentence within a list, the participant is asked to make a judgment as to whether it is a true sentence or not. At the end of each list, the participant must recall the final word of each sentence in that list. The competing demands aspect of the task, provided in this case by the ancillary true/false judgment, is a hallmark of working memory tasks, which impose substantial loads on both storage and processing. Participants' responses to both the verification and the recall components are given verbally. Sentence span score is defined as the total number of words correctly recalled. List length increases from two to six sentences, with three lists of each length.

Verbal memory: The digit span and non-word repetition subtests from the CTOPP (Wagner et al., 1999) were included in our test battery as well-established benchmark verbal memory measures.

Visuo-spatial memory: We assessed visuo-spatial memory using a computerized version of the Corsi blocks task (Corkin, 1974), implemented in Psyscope (Cohen, MacWhinney, Flatt, & Provost, 1993). The participant must reproduce increasingly long visually-presented sequences by tapping on an irregular arrangement of nine circles displayed on a computer touch-screen. For each trial, a sequence of three to nine of the displayed circles flashes briefly. Sequences start at length three and are presented in blocks of five at each length. Scores correspond to the longest sequence that a participant can successfully reproduce three times out of five.

Phonological awareness: The blending and elision subtests from the CTOPP (Wagner et al., 1999) were used to assess PA. Structurally, the PA components of the CTOPP and ToPEL (used in Experiment 1) are very similar. Both include elision and blending tasks, although the CTOPP focusses on segmental elements (phonemes) while the ToPEL includes syllabic/lexical elements as well as phonemic elements.

Decoding (pseudoword reading): The Woodcock–Johnson-III Tests of Achievement Word Attack subtest (Form A) is a measure of rule-based decoding skill (WJ-III; Woodcock, McGrew, & Mather, 2001). Based on pseudoword reading skill, it is a relatively pure index of orthographic–phonological decoding skill. Reliability across the age range of our study participants is 0.82 (McGrew & Woodcock, 2001).

Decoding (word reading): The WJ-III Word Identification subtest (Form A) is a measure of memory-based decoding skill based on word reading (Woodcock et al., 2001). This task primarily taps decoding skill, but it involves the decoding of known word forms rather than novel ones. Reliability across the age range of our study participants is 0.90 (McGrew & Woodcock, 2001).

Decoding composite: To create a composite decoding score that would weight the WJ-III Word Attack and Word ID tasks equally, raw scores from the two tasks were converted to *z*-scores, and then averaged to create a composite decoding score for each participant. (Note that the resultant composite is not actually a *z*-score itself.)

Intelligence: IQ was estimated using the two-task short form of the Wechsler Abbreviated Scales of Intelligence (WASI; Wechsler, 1999). The average reliability of these tasks is 0.96 (Wechsler, 1999).

Table IV. Summary of young adult data ($N = 45$).

Measure	Mean	SD	Maximum possible
Age (years)	19.52	2.37	–
Pseudoword repetition			
Raw score total	11.89	2.46	30
Rhyme items	5.96	1.57	15
Non-rhyme items	5.93	1.36	15
CTOPP			
PA standard score	86.40	19.35	–
PA total raw score	26.91	8.92	40
Blending items	13.27	4.74	20
Elision items	13.64	5.59	20
Digit span	16.33	3.40	21
Non-word repetition	9.00	2.36	18
WJ-III decoding			
Decoding composite	0.00	0.97	–
Word Attack	23.91	6.85	32
Word ID	64.34	7.73	76
Sentence Span	40.22	10.13	60
Corsi visuo-spatial memory	5.22	0.98	9
IQ	95.47	19.76	–

Results and discussion

Of the 50 individuals recruited, two failed to complete the protocol. Further, inspection of scatter plots and Mahalanobis distances, a metric for assessing multivariate normality, revealed three multivariate outliers among the remaining 48 cases (Tabachnick & Fidell, 2007, pp. 74-–75). These three are omitted from subsequent analyses. Thus, results reported below are based on data from 45 individuals (21 female). Table IV provides summary statistics for all measures. As shown, the PA skills of this group, indexed through CTOPP PA subtests, averaged lower than the normative sample (sample mean standard score = 86.40, SD = 19.35). We attribute this to the low reading skill demographic targeted for this study. This interpretation is supported by the relatively low word and pseudoword decoding scores for the group. The average word attack raw score of 23.91 and the average word ID score of 64.34 correspond to grade equivalent scores of 6.1 and 9.1, respectively. Summary statistics for the pseudoword repetition task indicate that the task is within the capabilities of the participants, but sufficiently challenging to avoid ceiling effects (mean total score = 11.89, SD = 2.46; min = 7; max = 17).

Further, a paired *t*-test of participants' performance on rhyme versus non-rhyme pseudoword repetition items does not indicate a difference for the two types of trials. On average, participants did equally well on rhyme and non-rhyme items. This suggests that rhyme interference effects observed in previous work (e.g. Mark et al., 1977; Olson et al., 1984; Shankweiler et al., 1979; Siegel & Linder, 1984) are not present in this sample of non-dyslexic but below-average young adult readers.

Table V displays correlations among the measured variables and age. In examining these associations, we note that CTOPP PA standard scores are correlated with all memory measures, including the visuo-spatial memory measure, but most strongly with sentence span ('CTOPP-PA: standard score' and 'Sentence Span', $r = 0.72$) However, most relevant to our purpose are correlations of pseudoword repetition scores with other memory and PA measures, shown in the grayed portion of the table. There, we observe that pseudoword repetition total scores correlate reliably with our decoding composite ('Pword rep: total score' and 'WJ3 decoding composite', $r = 0.32$, $p = 0.032$), PA ('CTOPP-PA: standard score', $r = 0.31$, $p = 0.039$), digit span ('CTOPP:

Table V. Correlations among Experiment 2 measures.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	Age	–													
2.	Pword rep: total score	–0.02	–												
3.	Pword rep: rhyme items	0.05	0.87***	–											
4.	Pword rep: non-rhyme items	–0.10	0.82***	0.42**	–										
5.	Pword rep: rhyme–non-rhyme	0.13	0.16	0.63***	–0.44**	–									
6.	CTOPP-PA: standard score	0.33*	0.31*	0.20	0.33*	–0.08	–								
7.	CTOPP-PA: elision items	0.24	0.25	0.13	0.31*	–0.13	0.88***	–							
8.	CTOPP-PA: blending items	0.28	0.29	0.26	0.24	0.05	0.81***	0.49**	–						
9.	CTOPP: digit span	0.23	0.73***	0.60***	0.63***	0.05	0.37*	0.33*	0.29	–					
10.	CTOPP: non-word rep	0.29	0.17	0.01	0.30*	–0.25	0.46***	0.32*	0.49**	0.44**	–				
11.	WJ3 decoding composite	0.39**	0.32*	0.28	0.26	0.06	0.79***	0.64***	0.65***	0.39**	0.32*	–			
12.	Sentence Span	0.11	0.33*	0.28	0.27	0.04	0.72***	0.59***	0.61***	0.27	0.12	0.71***	–		
13.	Corsi (visuo-spatial memory)	0.16	0.09	0.04	0.13	–0.07	0.54**	0.45**	0.49**	0.23	0.37*	0.50**	0.58***	–	
14.	WASI-IQ	0.28	0.32*	0.23	0.31*	–0.03	0.74***	0.58***	0.68***	0.38*	0.45**	0.74***	0.64***	0.71***	–

Note: Gray region highlights correlations of pseudoword-repetition-derived scores with other measures.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

digit span', $r = 0.73$, $p < 0.001$), sentence span ('Sentence Span', $r = 0.33$, $p = 0.028$) and IQ ('WASI-IQ', $r = 0.32$, $p = 0.034$), but surprisingly not with CTOPP non-word repetition ('CTOPP: non-word rep', $r = 0.17$, *NS*). Further, we note that participants' decoding scores were very strongly correlated with both PA ('WJ3 decoding composite' and 'CTOPP-PA: standard score', $r = 0.79$, $p < 0.001$) and sentence span ('WJ3 decoding composite' and 'Sentence Span', $r = 0.71$, $p < 0.001$), corroborating the importance of PA and PM in supporting the word decoding aspect of reading. It is of interest that correlations among decoding, memory and IQ measures found in this sample of young adults closely resemble findings reported by Braze et al. (2007), who studied reading-related skills in another young adult sample recruited by the same criteria. The similar results obtained in these two studies speak to the stability of these correlations in the population from which both samples were drawn, helping to validate the findings reported here.

We proceed by implementing a simple regression model targeting the pseudoword repetition total score with digit span, its highest zero-order correlate. From this starting point, we enriched the model with each additional memory measure and PA score, in turn. None of the additional variables increased prediction significantly, leaving only digit span as a predictor ($\beta = 0.729$, $p < 0.001$), accounting for 53.1% of variance in the pseudoword repetition total score.

Multiple regression was also used to evaluate the relationship between PA, pseudoword repetition and other verbal and non-verbal memory measures. We begin with a model that targets PA standard score with sentence span, its highest zero-order correlate, supplementing this base model sequentially with CTOPP digit span, CTOPP non-word repetition and Corsi blocks, and total scores from our experimental pseudoword repetition task. At each step, we retain only those variables that improve prediction significantly. The most parsimonious model to emerge from this series includes only sentence span ($\beta = 0.680$, $p < 0.001$) and CTOPP non-word repetition ($\beta = 0.375$, $p < 0.001$) as predictors, together accounting for 66.4% of variance in PA scores. Sentence span was the more important predictor variable, uniquely accounting for 45.6% of PA variance, while CTOPP non-word repetition uniquely accounted for 12.0% of PA variance, with the remaining 8.8% of variance shared between the predictors. This model affirms the association between aspects of verbal memory and PA. The result suggests that performance on the PA composite task depends on the simple ability to retain verbal material in memory, tapped primarily by the non-word repetition task, but more strongly on the ability to manipulate that material or shift the focus of attention over elements held in memory, an attribute tapped primarily by the sentence span index of verbal working memory.

Finally, given the central importance of skill in decoding for the development of literacy, and its relationship to these phonologically grounded capacities, we performed another regression analysis that targeted the Woodcock–Johnson decoding composite with the CTOPP PA standard score (its highest zero-order correlate), enriching this model sequentially with our memory and IQ measures, at each step retaining only those predictor variables which significantly improve the overall fit of the model. The resulting model included the CTOPP PA standard score ($\beta = 0.524$, $p < 0.001$) and the WASI-IQ score ($\beta = 0.377$, $p = 0.004$), but no measures of phonological or visuo-spatial memory. This model accounted for a total of 66.3% of the variance in decoding scores, with PA uniquely accounting for 12.3% of decoding variance, IQ uniquely accounting for 5.0% of decoding variance and the remaining 49.0% of decoding variance shared between the two predictors. Given that our PA composite is so closely tied to our memory measures, and that our decoding composite is also strongly related to some of our memory measures (as between decoding and sentence span, $r = 0.71$), this model suggests that the covariance between PA and PM is also shared with decoding.

General discussion

We introduced a pseudoword repetition task incorporating careful control over several lexical properties of the materials. Our primary goal was to describe an initial study with these materials with two widely separated age groups in order to establish their psychometric properties and their associations with other abilities important for reading. In each group, pseudoword repetition performance was significantly correlated with a standard measure of PA, even after taking age into account. The correlation between them is somewhat higher in the preschool cohort ($r = 0.49$) than in young adult cohort ($r = 0.31$). This is consistent with previous findings (Catts, Hogan, & Adlof, 2005; Scarborough, 2005). Both pseudoword repetition and PA have undeniable phonological components and so performance on each likely taps into some of the same underlying cognitive mechanisms. For example, high-level performance on PA tasks may result, in part, from better encoding and higher quality traces in PM. We interpret the correspondences between repetition and awareness task performance to be consistent with the hypothesis that verbal memory, as indexed by our novel pseudoword repetition task and other memory measures, is implicated in PA. Moreover, this relationship, which was present in both groups, supports the nomological validity of our experimental repetition task. We also note that, in the young adult cohort, pseudoword repetition is correlated with other measures of PM (digit span) and verbal working memory (sentence span), supporting convergent validity.

However, caution must be used in comparing pseudoword repetition scores for the two age groups. Consider that while there is considerable overlap in the distributions for the two groups (young adults' range 7–17; preschool children's range 3–11), test procedures did differ in ways that may have contributed to increasing the overlap. Perhaps the most important difference was that preschool children heard stimulus items three times before having to repeat them, while young adults heard each pseudoword but once. Hence, test procedure is confounded with age group. However, direct comparison of the two age groups was not a goal of the present study.

In regard to rhyme-based interference effects, data from this study indicate no difference between participants' recall performance on rhyming versus non-rhyming pseudowords in either age group. Previous studies have demonstrated rhyme interference in children aged 7–16 years (Mark et al., 1977; Olson et al., 1984; Shankweiler et al., 1979; Siegel & Linder, 1984; also see Conrad, 1971), with the effect decreasing between 13 and 16 (Olson et al., 1984; Siegel and Linder, 1984). Both age groups surveyed in this study were outside this range. Our findings, in conjunction with the previous studies, might suggest that the interference effect first appears in children between the ages of 5 and 7 years, as Conrad (1971) found, and then falls off in late adolescence. Alternatively, our study may have lacked sufficient power to detect rhyme effects. Additional research is necessary to decide which of these possibilities is correct.

Finally, the results of Experiment 2 showed substantial relationships between decoding and phonologically grounded capacities as hypothesized in that both PA and PM were closely related to decoding performance. These results also demonstrated tight links between PA and PM, suggesting that the influences of these capacities on decoding skill may not be independent, contrary to some previous findings (for example, De Jong & Van Der Leij, 1999; Hansen & Bowey, 1994; Mann & Liberman, 1984).

Summary and conclusions

The purpose of this study was to develop a suitable tool to investigate the relationship between PM and reading skill that could validly be applied across a wide range of the developmental spectrum. Pseudoword repetition has shown promise in earlier research as a means for investigating the memory requirements for reading, but previously used tests of pseudoword repetition are uncontrolled in ways that make the findings difficult to interpret, as well as being unsuitable for use at widely separated ages and levels of cognitive development. Accordingly, we created a new instrument that is controlled in relevant phonetic and linguistic dimensions and we tested it with an unselected group of typically developing preschoolers and a young adult group exhibiting a wide range of reading (decoding) skill. Both groups received the same test materials with age-appropriate modifications of the test procedure.

The pseudoword test was considered to be valid at the preschool, pre-literacy level (Experiment 1) because scores showed good distributional properties and yielded significant correlations with PA, one of the most important indicators of reading readiness. Absence of floor or ceiling effects suggests that the task may be useful with younger children or those with clinically significant language issues, although this surmise will require further research for confirmation. The pseudoword task also proved valid in the adult cohort (Experiment 2), where it was found to be correlated with measures of PA, as well as other memory measures (with exception of CTOPP non-word repetition) and a decoding-based measure of reading skill. A shared relationship with PA is the common denominator between the results of Experiments 1 and 2. This finding is of theoretical and practical significance because PA has repeatedly been shown to be both a prerequisite and a predictor of reading skill as well as an enduring component of reading skill, once established. The ability to use identical, carefully controlled, pseudoword stimuli across a wide span of the developmental continuum will enhance our capacity to track changes in relations among cognitive skills critical to the acquisition of language and literacy in both typically developing and clinical populations.

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Appendix: Experimental pseudoword repetition materials and neighborhood statistics

Neighborhood statistics for strong syllables in pseudoword repetition materials.

Length	Condition	IPA Gloss		Neighborhood size	Neighborhood frequency	Length	Condition	IPA Gloss		Neighborhood size	Neighborhood frequency
0	NA	nim		20	1544						
0	NA	faʊn		18	1873						
0	NA	fip		19	1367						
1	NA	bop	fə	20	1119						
1	NA	hoʧ	tə	16	1789						
1	NA	θut	sə	14	1098						
2	r	bog	zə	16	1157	2	n	moɪt	sə	14	1222
2	r	hog	zə	14	1747	2	n	tev	də	15	1773
2	r	paɪf	pə	15	937	2	n	wig	zə	15	812
2	r	daɪf	pə	17	1018	2	n	fum	zə	17	980
2	r	tiv	bə	17	646	2	n	boch	tə	17	685
2	r	kiv	bə	18	802	2	n	dep	sə	18	874
3	r	ʧop	fə	17	727	3	n	num	zə	16	640
3	r	gop	fə	18	924	3	n	toɪn	zə	19	961
3	r	bop	fə	20	1119	3	n	fip	sə	19	1367
3	r	baɪv	bə	14	603	3	n	def	pə	15	607
3	r	gaɪv	bə	14	1618	3	n	paʊn	və	15	1616
3	r	paɪv	bə	16	622	3	n	ʧim	və	16	743
3	r	diʧ	tə	14	690	3	n	hif	pə	18	810
3	r	kiʧ	tə	20	737	3	n	bov	bə	13	649
3	r	niʧ	tə	18	915	3	n	vik	fə	19	811
4	r	ʃiv	bə	14	379	4	n	zot	sə	12	376
4	r	div	bə	14	727	4	n	dif	pə	15	528
4	r	niv	bə	16	985	4	n	gom	zə	16	965
4	r	kiv	bə	18	802	4	n	dep	sə	18	874

4	r	ʧep	fə	15	530	4	n	waɪb	zə	14	693
4	r	hep	fə	20	750	4	n	tup	fə	18	743
4	r	tɹep	fə	14	453	4	n	gɹip	fə	16	469
4	r	step	fə	16	840	4	n	ʃom	və	16	757
4	r	gɹaʊn	və	14	184	4	n	kɹem	zə	14	184
4	r	faʊn	və	18	1873	4	n	hoʧ	tə	16	1789
4	r	ɹaʊn	və	19	1872	4	n	θet	sə	16	1741
4	r	paʊn	və	15	1616	4	n	nim	zə	20	1544
5	r	gum	zə	16	444	5	n	foɪt	sə	14	406
5	r	ʧum	zə	16	475	5	n	noʧ	tə	14	481
5	r	kɹum	zə	13	111	5	n	fɹit	sə	13	117
5	r	ʃum	zə	16	438	5	n	ɹug	zə	16	452
5	r	fum	zə	17	980	5	n	bop	sə	20	1119
5	r	fob	zə	10	109	5	n	fup	fə	10	164
5	r	nob	zə	15	461	5	n	gok	sə	16	469
5	r	kob	zə	16	286	5	n	pib	zə	16	307
5	r	hob	zə	14	1747	5	n	gaɪv	bə	14	1618
5	r	gɹob	zə	13	153	5	n	spot	sə	13	174
5	r	gaɪf	pə	13	918	5	n	faɪb	və	11	814
5	r	baɪf	pə	15	922	5	n	gom	zə	16	965
5	r	ʧaɪf	pə	12	927	5	n	fiʧ	tə	13	1066
5	r	haɪf	pə	15	1428	5	n	gov	bə	14	1430
5	r	saɪf	pə	20	1661	5	n	θit	sə	17	1563
6	r	gim	zə	11	663	6	n	bof	pə	10	644
6	r	fim	zə	18	1891	6	n	faʊn	və	18	1873
6	r	jim	zə	16	647	6	n	saɪb	və	15	723
6	r	nim	zə	20	1544	6	n	fip	fə	19	1367
6	r	ʃim	zə	17	701	6	n	ʧop	fə	17	727
6	r	ʧim	zə	16	743	6	n	zik	sə	19	807

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Length	Condition	IPA	Gloss	Neighborhood size	Neighborhood frequency	Length	Condition	IPA	Gloss	Neighborhood size	Neighborhood frequency
6	r	baɪp	fə	15	295	6	n	huk	sə	15	266
6	r	daɪp	fə	16	428	6	n	fetʃ	tə	14	310
6	r	naɪp	fə	15	1295	6	n	maɪb	və	10	1144
6	r	kaɪp	fə	16	773	6	n	nif	pə	16	764
6	r	ʃaɪp	fə	12	531	6	n	θom	zə	12	546
6	r	maɪp	fə	14	1439	6	n	maɪv	bə	15	1935
6	r	gef	pə	16	399	6	n	tig	zə	16	379
6	r	def	pə	15	607	6	n	fop	fə	16	591
6	r	ʃef	pə	15	189	6	n	lug	zə	14	172
6	r	stef	pə	14	850	6	n	stit	sə	14	838
6	r	kef	pə	17	1323	6	n	bog	zə	16	1157
6	r	gɹef	pə	13	1066	6	n	plem	zə	14	1002

Note: In the table, rhyming items (at left) are paired with non-rhyming items (at right) and matched for neighborhood statistics; blank lines separate pseudoword items. *t*-Tests reveal no significant difference between neighborhood sizes ($t = –0.555$, $p = 0.58$) and summed frequencies of neighbors ($t = –0.022$, $p = 0.99$) for rhyming versus non-rhyming items. There were also no significant differences in neighborhood sizes or summed frequencies between rhyme conditions at any length (by *t*-test).