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Dynamic relationships between phonological memory and reading: a five year longitudinal study from age 4 to 9

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Research Highlights

- Phonological memory tasks that loaded strongly on serial order memory (verbal short-term memory) were separable from nonword repetition, each showing a unique relationship with reading.
- Verbal short-term memory directly predicted early reading (by supporting sequential letter-by-letter decoding), but reading did not predict verbal short-term memory.
- Reading predicted nonword repetition via phoneme awareness (by promoting phonemically-detailed phonological representations), and directly (by supporting the use of orthographic cues when repeating new words).
- Indirect effects from both constructs to reading, via phoneme awareness, suggest that good phonological memory stimulates phonemically-detailed representations through repeated encoding of complex verbal stimuli.

Abstract

We reconcile competing theories of the role of phonological memory in reading development, by uncovering their dynamic relationship during the first five years of school. Phonological memory, reading and phoneme awareness were assessed in 780 phonics-educated children at age 4, 5, 6 and 9. Confirmatory factor analyses demonstrated that phonological memory loaded onto two factors: verbal short-term memory (verbal STM; phonological tasks that loaded primarily on serial order memory), and nonword repetition. Using longitudinal structural equation models, we found that verbal STM directly predicted early word-level reading from age 4 to 6, reflecting the importance of serial-order memory for letter-by-letter decoding. In contrast, reading had no reciprocal influence on the development of verbal STM. The relationship between nonword repetition and reading was bidirectional across the five years of study: nonword repetition and reading predicted each other both directly and indirectly (via phoneme awareness). Indirect effects from nonword repetition (and verbal STM) to reading support the view that phonological memory stimulates phonemically-detailed representations through repeated encoding of complex verbal stimuli. Similarly, the indirect influence of reading on nonword repetition suggests that improved reading ability promotes the phoneme-level specificity of phonological representations. Finally, the direct influence from reading to nonword repetition suggests that better readers use orthographic cues to help them remember and repeat new words accurately.

Keywords: Verbal short-term memory, nonword repetition, reading, phonological, longitudinal, development

Dynamic relationships between phonological memory and reading: a five year longitudinal study from age 4 to 9

There is increasing awareness of the benefits of literacy for fundamental cognitive skills (Kolinsky, 2015). Yet, traditionally, the focus has been in the opposite direction - on how cognitive skills shape and predict literacy development (Hulme & Snowling, 2013; Melby- Lervåg, Lyster, & Hulme, 2012a). Three cognitive skills have been identified as the most robust predictors of word reading (Wagner & Torgesen, 1987): phoneme awareness (the manipulation of sounds in spoken words), phonological memory (otherwise known as verbal short-term memory; the temporary and limited-capacity storage of verbal information), and rapid automatized naming (RAN; timed retrieval and articulation of phonological representations from long term memory). Children with reading impairment typically show deficits in one or more of these skills (Peterson & Pennington, 2012), and all three have been shown to predict reading accuracy longitudinally from pre-school onwards (de Jong & van der Leij, 1999; Hulme & Snowling, 2013). Alternatively, poor phonological processing may be a consequence, not a cause of reading impairment (Huettig, Lachmann, Reis, & Petersson, 2018), with literacy influencing phonological skills as much, if not more, than phonological skills influence literacy (Dehaene et al., 2010; Kolinsky, 2015; Rastle, McCormick, Bayliss, & Davis, 2011).

Consisitent with this view, there is evidence of a bidirectional relationship between phoneme awareness and reading (Perfetti, Beck, Bell, & Hughes, 1987; Wagner, Torgesen, & Rashotte, 1994), and between RAN and reading (Peterson et al., 2017). These studies showed that reading both predicted and was predicted by phoneme awareness and RAN, and that the nature of these relationships changed over the course of early to intermediate reading development. A bidirectional relationship between phonological memory and reading may also exist, but evidence for this is not clear, and potentially complicated by developmental changes in both constructs (see Demoulin & Kolinsky, 2015 for a review).

The question of how phonological memory and reading interact across development is central to reconciling important theoretical debates in the field. Two main hypotheses have been proposed, a) that phonological memory predicts reading via shared variance with phoneme awareness due to a mutual reliance on underlying phonological representations (Melby- Lervåg et al., 2012a) or that b) phonological memory contributes to reading over and above phoneme awareness due to its role in retaining and ordering sounds during the decoding process (Gathercole & Baddeley, 1993; Martinez Perez, Majerus, & Poncelet, 2012). There are also questions about whether reading confers advantages on memory. One theory suggests that reading enhances phonological memory by promoting more fine-grained phonological representations (Muneaux & Ziegler, 2004; Ziegler, Muneaux, & Grainger, 2003). Others, however, find a near-perfect longitudinal stability of phonological memory, uninfluenced by reading growth (Wagner et al., 1994, 1997). Crucially, although these theories focus on development, there is little empirical evidence on how these relationships change over time. By investigating bidirectional links between phonological memory and reading within a large-scale, longitudinal latent variable study, the current study provides the first developmental evidence to test these competing theories. Our work represents a significant advance on previous studies in the field such as Wagner et. al., (1994, 1997), and Nation and Hulme (2011) by 1) testing links between phonological memory and reading within models that include mediating links with phoneme awareness, and 2) covering a five year developmental period (age 4 to 9, in order to test developmental changes).

The contribution of phonological memory to word reading

The dominant view in the literature is that phonological memory influences reading via shared variance with phoneme awareness. Specifically, both phonological memory and phoneme awareness tasks depend upon the same underlying phonological representations, and it is the quality of these representations, rather than our ability to remember them, which drives the association with reading (Hulme & Roodenrys, 1995; McDougall, Hulme, Ellis, & Monk, 1994; Melby- Lervåg et al., 2012a). A large body of research has established the importance of the quality of underlying phonological representations for word-level reading (as exemplified by the 'phonological quality' hypothesis Swan & Goswami, 1997, also see Hulme & Snowling, 2013 for a review). The quality of phonological representations is defined by the extent to which they are represented accurately at the phoneme-level, as tapped by phoneme awareness tasks (e.g., Fowler, 1991). In turn, having high quality phoneme-level representations is essential to reading development (see Quinn, Spencer, & Wagner, 2015 for a review).

Seminal work by Wagner and colleagues (1994, 1997) supports the view that phonological memory and phoneme awareness draw on the same underlying phonological representations. The authors followed a cohort of just over 200 children in the US, followed from Kindergarten to 4th grade. Structural equation models showed that a latent phonological memory variable (comprised of a digit span and a sentence memory measure), did not predict word reading accuracy across the five years over and above phonological awareness and rapid naming, which alone were significant predictors. However, phonological memory and phonological awareness were strongly correlated, suggesting that a shared reliance on phonological representations might mediate the relationship between phonological memory and reading. More recent support for the theory comes from a meta-analysis of 135 correlational studies by Melby- Lervåg et al. (2012a), showing that verbal short-term memory (made-up of tasks where children were instructed to repeat a spoken list of words) did not uniquely predict reading beyond that explained by phoneme awareness, across the school years. This led to the conclusion that the impact of verbal-short term memory on reading is limited to shared variance with phoneme awareness. The meta-analysis, however, did not distinguish between concurrent and longitudinal studies or investigate changes in the relationships over time.

There are good reasons to expect a concurrent relationship between phonological memory and phoneme awareness (e.g. as found in Lervåg Bråten, & Hulme, 2009) because of their mutual reliance on the quality of the same phonological representations. For example, during a nonword repetition task, (e.g. say the word 'dopelate'), one must encode and retrieve a phonological representation of 'dopelate' in memory before pronouncing it. Then, during a phoneme awareness task (e.g. what is 'dopelate without the /d/), one must encode and retrieve the same representation prior to deletion. However, it is less clear whether we should also expect a longitudinal relationship. Melby-Lervåg and Hulme (2010) showed that training children to manipulate phonemes in unfamiliar words improved their serial recall of the same words, suggesting that improving the phoneme-level accuracy of phonological representations promotes the development of phonological memory. We propose that a developmental relationship from phonological memory to phoneme awareness is also plausible: having good phonological memory skills facilitates repeated encoding of increasingly complex verbal stimuli which supports the development of increasingly fine-grained phonological representations. For example, it has been suggested that repeating nonwords involves the generation of an abstract phonological 'frame' based on existing items that are structurally similar. The new representation then marks an increase in detail at the structural (phoneme and large segment) level (Gathercole, Willis, Emslie, & Baddeley, 1991). However, to our knowledge there is not, as yet, any longitudinal evidence to support these assertions.

To generate predictions amenable to statistical testing within the context of a longitudinal study, we propose a series of mediated pathways over time: phonological memory predicts phoneme awareness (due to repeated encoding of complex verbal stimuli supporting the development of phonemically-structured representations), then in turn, phoneme awareness predicts reading (due to phonemically-structured representations supporting the development of word reading).

An alternative theory argues that phonological memory plays an independent role in reading development, unique from phoneme awareness (Gathercole & Baddeley, 1993). The argument is that phonological memory is necessary to store sounds while learning letter–sound correspondences, and subsequently to store sound segments produced during the decoding of words. For example, phonological memory is needed when learning the letter sounds ‘c,a,t’, then again, to store and retrieve these phonemes when decoding the word ‘cat’. This process is independent from the stages of decoding that require phoneme awareness, namely, the accessing and blending of phonemes (Beneventi, Tønnessen, Ersland, & Hugdahl, 2010; Wagner & Torgesen, 1987). Evidence in support of this theory comes from research showing that measures of phonological memory are independent predictors of reading from those of phoneme awareness. For example, with regard to nonword repetition (Muter & Snowling, 1998) and a broader phonological memory factor (Dufva et al., 2001).

A related argument has been put forward by Martinez-Perez and colleagues (2012). They found that tasks specifically designed to tap memory for serial order (recognition of the sequential order of digits) predicted independent variance in nonword decoding in beginning readers, over and above phoneme awareness (Binamé & Poncelet, 2015; Martinez Perez et al., 2012; Nithart et al., 2011). Martinez Perez et al. (2012) claim that serial order memory (the component of verbal short-term memory that encodes item order) is required ‘online’ during the decoding process through the temporary storage of the ‘ordered succession of the successive products of the letter-to-sound conversion processes’ (p. 710). Applied longitudinally, proponents of these latter two theories (Gathercole & Baddeley, 1993 and

Martinez-Perez et al., 2012) suggest that phonological memory (particularly serial order memory) has an independent influence on reading development over and above phoneme awareness. A key prediction common to both theories is that serial-order memory should be most predictive of reading early on in reading development, particularly when children are learning to translate letters into sounds and blend them together to pronounce the word (the alphabetic phase; Ehri, 2017).

Central to the work of Martinez-Perez and colleagues is the conceptualization that phonological memory comprises two components: item memory (the ability to store verbal information via temporary activation of phonological representations), and serial order memory (the ability to reactivate the order of activation of these representations) (Majerus et al., 2010; Majerus et al., 2006). Tasks which require repetition of familiar items (such as forwards digit span or word span) tap more strongly into the construct of serial order memory as they engage existing long-term phonological representations. In contrast, tasks which involve unfamiliar items such as nonword repetition, load more heavily on item memory as they necessitate the creation of new representations. However, previous research is mixed as to whether tasks which rely more strongly on item memory are analysed separately from more traditional serial order tasks. Some find that nonword repetition loads on the same factor as serial order tasks (Alloway, Gathercole, Willis, & Adams, 2004), others place it on a separate factor for theoretical reasons (Gathercole & Pickering, 2000), while others examine it in a separate study (e.g., Gathercole, 1995; Nation & Hulme, 2011). In the current study, we will test whether nonword repetition loads on the same or a different factor from two other measures of phonological memory (that tap serial order: the repetition of familiar items), with a view to assessing the combined or separate relationship with reading.

Consequences of reading for phonological memory

A well-established view is that reading predicts phonological memory because learning to read in an alphabetic orthography promotes more phonemically segmented phonological representations (Kolinsky, 2015; Ziegler et al., 2003). In turn, phonemically structured representations support the ability to access and encode verbal information, improving verbal short-term memory (Melby-Lervåg & Hulme, 2010). Ziegler, Muneaux and Grainger (2003) and Muneaux and Ziegler (2004) proposed a mechanism to explain how the specification of phonological representations improves with literacy experience. They describe learning to read and write as stimulating a process similar to 'lexical restructuring' (growth in vocabulary causing the restructuing of phonological representations, to better distinguish between similarly sounding words, Metsala & Walley, 1998). Namely, as children learn the mappings between letters and sounds, words that are similar in both sound and spelling become more finely specified to reflect this phoneme-level knowledge. Because orthographic information triggers improved specification of phonological representations, this is akin to 'orthographic restructuring' of phonological representations.

In line with this theory, Nation and Hulme (2011) measured the influence of reading on the specificity of phonological representations, as measured by nonword repetition tasks. They used structural equation modeling to show that in a group of 215 children, word reading at age 6 predicted nonword repetition at age 7 (after controlling for oral language skills), but not vice versa (they suggest this was because word reading was so stable, there was little variance left to explain.) However, as phoneme elision was not partialed out in the longitudinal analyses it is unclear whether reading was acting directly on nonword repetition performance, or indirectly via phoneme awareness.

In order to generate developmental hypotheses consistent with this theory, we propose a series of mediated pathways whereby reading predicts phoneme awareness longitudinally (to reflect ‘orthographic restructuring’ of phonological representations), which in turn, predicts phonological memory at the next time point (to reflect the effect of phonemic restructuring of representations on phonological memory). Finally, because the influence of reading on phonological memory likely depends on the extent to which reading draws on phonological representations, this relationship is predicted to diminish as children learn to recognize more words by ‘sight’, and reading depends less on the quality of phonological representations (Ehri, 2017).

It is not clear whether reading would also influence phonological memory measures that do not involve a strong reliance on the quality of phonological representations (e.g. tasks that load mainly on serial order memory such as those involving repetition of familiar items). Ellis (1990) found that reading predicted digit span from age 5 to 7, whereas Wagner et al., (1994, 1997) found that it did not. A key limitation of previous studies is that they did not test whether the relationship changed for different measures of phonological memory within the same sample. We address this potentially important issue by assessing multiple measures of verbal memory (nonword repetition and two tasks involving repetition of familiar items) so that their potentially dynamic relationships with reading over time can be examined. Importantly, our study is the first to comprehensively examine these relationships in a sample of children educated using systematic synthetic phonics. We know that children receiving intensive synthetic phonics teaching rely more heavily on phonological awareness skills for reading (Shapiro & Solity, 2016), so the influence of reading on phonological tasks is also likely to be stronger. Consequently, we may expect to find stronger links between phonological memory, phoneme awareness and reading in our study that those found in children taught using a whole language method (such as the sample reported in Wagner et al., 1994, 1997).

The current study

Our aim was to investigate hypothesised bidirectional relationships between phonological memory and word-level reading, and examine how these relationships changed over time. The following questions were addressed:

1. Does phonological memory, as measured by serial-order repetition of familiar items (hereafter verbal short-term memory; VSTM), form a separable construct from nonword repetition (NWR)?

Then, depending on the answer to 1.

2. Does VSTM/NWR predict reading longitudinally, and if so, is this effect direct or indirect, mediated by phoneme awareness?
3. Does reading predict VSTM/NWR longitudinally, and if so, is this effect direct or indirect, mediated by phoneme awareness?
4. Do the relationships in 2) and 3) change over time as reading skills develop?

Method

Data were collected as part of a large-scale longitudinal study where children were assessed for phonological memory, word-level reading and phoneme awareness at four time points over 5 years when the mean age of the cohort at each time point was 4yr 8m, 5yr 3m, 6yr 2m, and 9yr 3m.

Participants

All children enrolled in Reception classes across 16 schools in the Birmingham area of the UK were invited to participate in the Aston Literacy project (see www.aston.ac.uk/alp). Parents were sent a letter informing them about the study and providing the opportunity to opt-out, and consent was given by the Headteacher. Complete or majority complete data were obtained for 780 children at the beginning of the first year of formal schooling (T1, age 4;8

range 4;0-5;2), 765 at the end of the first year (T2, age 5;3 range 4;8-5;11), 695 at the end of Year 1; the second year of schooling (T3, age 6;2, range 5;8-6;10), and 555 at the end of Year 4; the fifth year of schooling (T4, age 9;3, range 8;8 – 9;10). The principle reason for not recapturing a child at re-test was moving school (note that children dispersed from infant to junior schools between Times 3 and 4, increasing attrition).

Analyses were conducted on the full sample of 780 children, with missing data imputed using maximum likelihood estimation[2]. Data were missing at the child-level for; T2 age 5 = 1.9%, T3 age 6 = 10.9%, T4 age 9 = 28.8%, equivalent to 8.3% attrition per year. At time 1, the sample consisted of 51% boys. 10% children spoke English as an additional language, and 3 children had a statement of special educational needs.

Tasks

Children were tested individually in a quiet area in school. Memory tasks (apart from digit span) and phoneme awareness tasks were administered through headphones (Sennheiser, HD 25-111). Phoneme repetition was programmed using the ‘pygame’ module in Python (Sweigart, 2010), while nonword repetition and phoneme awareness tasks were programmed in Eprime (Schneider, Eschman, & Zuccolotto, 2002).

At times 1-3, children completed the CPSAS (Component Phonological Skills Assessment Scales) (Cunningham, Witton, Talcott, Burgess, & Shapiro, 2015), as well as standardized measures of word-level reading. At time 4, children completed a set of equivalent phonological measures appropriate to their age. Other tasks were also included that related to the longitudinal prediction of reading difficulties, but these will be reported separately.

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[2] Analyses on the 555 children (71.2% of T1 sample) for whom we had complete or majority complete data for at every time point showed the same pattern of findings.

Phonological memory.

T1-T4: Digit span. In the Recall of Digits Forwards subtest from the British Ability scales-2 school age tests, the experimenter read out sequences of digits at a rate of 2 per second, and the child repeated them back. Two scores were derived: total number of items correct, and digit span (defined as obtaining =>4/5 correct for a particular sequence length).

T1-T3: Phoneme repetition (CPSAS). Each child was presented with 21 sequences of the stop consonants /g/, /k/, /p/ (selected because they are the earliest acquired consonants, Kilminster & Laird, 1978), and asked to repeat them back. It was established that the child could pronounce each of the phonemes clearly before the test was administered. There were three parts: part one had 9 items of two phonemes per sequence, part two had 6 three-phoneme items, and part three had 6 four-phoneme items. Each phoneme was presented for 500ms, with an inter-stimulus interval of 300ms. See Appendix A for items.

T1-T3: Nonword repetition (CPSAS). This consisted of two sets during which children were asked to repeat back single nonwords as accurately as possible.

Set 1: Nine single-syllable nonwords (6 CVC, 3 CCVC) taken from the YARC sound isolation task (Snowling et al., 2009).

Set 2: Three more single-syllable nonwords (1 CVC, 2 CVCC), followed by 9 multi-syllabic words (2 two-syllable, 2 three-syllable, 2 four-syllable, 3 five-syllable) (taken from the Children's Test of Nonword repetition; Gathercole, Willis, Baddeley, & Emslie, 1994). Repetition attempts were scored as either correct or incorrect. See Appendix A for items.

T4: Nonword repetition (TOPHS). An adapted version of the nonword repetition task (the 'Test of Phonological Structure' (TOPHS), Van Der Lely & Harris, 1999) was completed. This version contained 48 of the 96 nonwords contained in the original TOPHS, derived from four basic CVCV nonwords. Nonwords were selected with a range of complexities (number of marked structures) and lengths (number of syllables); 24 simple and 24 complex:

Simple nonwords. The child was asked to repeat 12 simple (0-2 marked structures) nonwords.

Complex nonwords. The child was asked to repeat 12 complex (3-5 marked structures) nonwords. Simple and complex words for matched for length.

Repetition attempts were scored as either correct or incorrect. There was a split-design such that nonword repetition data were only collected for 229 children at T4. See Appendix A for items.

Phoneme awareness.

T1-T3: Phoneme isolation and deletion (CPSAS). These two tasks involved the same stimuli and structure as the CPSAS nonword repetition task. Nonword repetition was administered first, followed by isolation, then deletion. In part one, children were asked to isolate/delete the first phoneme in the nonword. In part two, they were asked to isolate/delete the final phoneme.

T4: Phoneme deletion (PhAB2). The phoneme deletion task from the Phonological Assessment Battery 2nd edition (Gibbs & Bodman, 2014) was administered. The test consisted of three parts with six items each. Children were asked to delete 1) the final consonant from a three-phoneme word, 2) the initial consonant from a four-phoneme word, and 3) the second phoneme of an initial consonant digraph from a four-five phoneme word.

Reading.

T1-T2: Letter-sound knowledge. Children were tested on the LeST (Larsen, Cohnen, McArthur, & Nickels, 2011). Lower-case letters were presented on sheets: there were 25 single letters (q was not included) and 26 digraphs (e.g., *ee*, *ou*). Children were asked to say what sound each grapheme made.

T1-T4: Word-level reading. The word reading sub-test from the British Ability Scales-2 school-age battery (Elliot, Smith, & McCulloch, 1996) was administered. Children were asked to read a list containing a mixture of regular (43) and irregular (47) words. In addition, the Diagnostic Test of Word Reading Processes (Forum for Research in Language and Literacy, 2012) was completed. This consisted of three lists of 30 stimuli, 1) regular words, 2) nonwords, and 3) exception words.

Results

Table 1 shows descriptive and normality statistics and internal reliabilities for all measures collected. Note that there are five tasks not included in the analyses due to developmentally appropriate floor/ceiling effects, highlighted in light grey. The dataset displayed multivariate normality (critical ratio of multivariate kurtosis = 5.72), indicating appropriateness for multivariate analysis (Tabachnik & Fidell, 2019). Reliabilities were medium/high (> .70). Table 2 shows the estimated correlations between latent variables which reveals medium-high correlations between the same constructs over time (see Appendix B for correlations between indicator variables). All models were built in AMOS 26.0 (IBM, 2019) using maximum likelihood estimation.

Confirmatory factor analyses: the separability of VSTM and nonword repetition

Confirmatory factor analysis (CFA) was used to address our first research question: whether serial-order repetition of familiar items (digit span and phoneme repetition) formed a separable construct from nonword repetition. We compared two latent variable models at each time point; a single factor model in which digit span, phoneme repetition and nonword repetition (Set 1 and Set 2) all loaded on the same factor and a two-factor model which placed nonword repetition on a separate factor. As phoneme repetition was not measured at T4, digit span was split to create two indicators (total correct for odd and even items). CFAs were performed to determine the best fitting model (see Figure 1). At each time point, the two factor model showed a significantly better fit to the data ($\Delta\chi^{2s} > 49$ (1), $p < .001$), so the two-factor model was adopted for all subsequent analyses (see supporting information for fit indices). For ease of interpretation, the factor consisting of digit span and phoneme repetition was named the verbal short-term memory (VSTM) factor.

Longitudinal constructs. Examination of the longitudinal correlations between indicator variables of nonword repetition revealed a particularly low correlation between set 1 nonword repetition T2 to T3. We therefore explored the item data and found deletion of two items at these time points improved this longitudinal correlation. Therefore the indicators without these items were used in the main models. Due to word-level reading being mainly at floor at T1 (as to be expected for children at the start of the first year of school), reading was indexed by letter-knowledge (LK) at T1 (split into vowels and consonants), and at T2-T4 by total score on the BAS and DTWRP. For phoneme awareness, children were at floor for phoneme deletion at T1 and T2, therefore, for consistency, phoneme awareness was indexed by odd and even items for phoneme isolation at T1-T3. At T4, there was only one measure of phoneme awareness (phoneme deletion), therefore it was indexed by odd and even items.

We tested for factorial invariance across time by testing longitudinal models of each construct (Reading, PA, VSTM and NWR) using standardised scores for the indicator variables. We found that in all but one case, constraining the factor loadings between consecutive time points led to a non-significant worsening of model fit ($p > .05$). The only significant change observed was between VSTM T3 – T4 (presumably because the indicators were different). Nevertheless, the stability of the autoregressor was high (see Model 3; Figure 3). This demonstrates that we were measuring the same constructs over time.

Construction of our longitudinal structural models confirmed the structure of our reading and phoneme awareness latent variables. These models are shown in Figures 3 and 4.

Both structural models showed a reasonable to good fit to the data (see next section), confirming the viability of our latent constructs.

Longitudinal structural models (Cross-lagged latent panel models)

Structural equation modeling was used to model bidirectional relationships between VSTM and reading, and NWR and reading, while accounting for the potential mediating effects of phoneme awareness. Two hypothesised models were built to test the longitudinal relationships described in research questions 2 – 4 (see Figure 2). Following calculation of each hypothesised model, insignificant links were systematically removed in order to achieve the most parsimonious fit. The final models (Model 3 and Model 4) are displayed in Figures 3 and 4.

VSTM and reading. Model 1 displayed nine links that were non-significant; PAage4 to VSTMage5, -.10, *p* =.08, LKage4 to VSTMage5, -.08, *p*= .10, PA age5 to VSTMage6, .01, *p*= .74, READage5 to PAage6, .01, *p* =.81, READage5 to VSTMage6, -.05, *p*= .18, VSTMage6 to PAage9, .07, *p*= .49, VSTMage6 to READage9, .02, *p* =.56, PAage6 to VSTMage9, -.03, *p* =.60, and READage6 to VSTMage9, -.03, *p*= .60. Insignificant links were removed with no significant change in model fit, $\Delta\chi^2(9) = 13.7$, *p* =.13. Therefore the model without these links was accepted (Model 3, Figure 3). The final model displayed a good fit to the data, $\chi^2(231) = 652.70$, *p* >.001, NFI= .952, IFI= .968, CFI= .968, RMSEA= .048 (CI .044 - .053).

Model 3 shows that VSTM predicted word-reading directly from age 4 to 5, and from age 5 to 6. VSTM also predicted word-reading indirectly (via PA) from age 4 to 5 to 6, and from age 5 to 6 to 9. There were no significant links from word-reading to VSTM.

Nonword repetition and reading. Model 2 displayed four links that were non-significant; NWRage4 to READage5, .00, p =.93, READage5 to PAage6, .01, p =.77, READage5 to NWRage6, -.01, p =.89, NWRage6 to PAage9, -.17, p =.10. Removal of these links resulted in a non-significant change in model fit $\Delta\chi^2(4) = 2.7$, $p = .61$. Therefore the model without these links was accepted. In addition, there were two negative and significant links; NWRage6 to NWRage9, -.18, p = .05 and NWRage6 to READage9, -.15, p <.01. These links were removed on a priori grounds; negative relationships between these variables were not theoretically plausible (supported by the fact that the estimated correlations between NWRage6 and NWRage9 and NWRage6 and READage9 were .30 and .24 respectively, p <.01). The negative coefficients were likely caused by a confounding effect, something that can happen in complex models where multiple predictor variables have high levels of overlapping variance (Baguely, 2016). The final model, Model 4, is shown in Figure 4. Model 4 displayed a good fit to the data, $\chi^2(228) = 618.84$, p >.001, NFI= .947, IFI= .966, CFI= .965, RMSEA= .047 (.042 - .051).

Model 4 shows that NWR predicted word-reading directly from age 5 to 6 and indirectly (via PA) from age 4 to 5 to 6, and 5 to 6 to 9. In the opposite direction, letter-knowledge predicted NWR directly from age 4 to 5 and word-reading predicted NWR directly from age 6 to 9. Letter-knowledge also predicted NWR indirectly (via PA) from age 4 to 5 to 6.

Discussion

We have provided a comprehensive investigation of developmental changes in the relationship between reading and different aspects of phonological memory. Evidence was found of a dynamic relationship from beginning to intermediate readers, which reconciles the differences between domimant theories, and has important implications for practice. First, we found that different aspects of phonological memory were separable, and showed different relationships with reading over time. Specifically, phonological memory tasks that tapped memory for serial order (VSTM) were directly predictive of reading (supporting Gathercole and Baddeley, 1993 & Martinez-Perez et al., 2012's independent influence theory), but only during the first two years of school. This highlights the developmental specificity of these relationships, and the need for longitudinal data to separate this early stage of reading. Both aspects of phonological memory (VSTM and nonword repetition) also indirectly contributed to reading over time, via phoneme awareness (broadly supporting Melby- Lervåg et al's 2012a shared variance theory).

In the opposite direction, we found that reading had a dynamic, longitudinal influence on nonword repetition. Specifically, letter-knowledge had an indirect influence on nonword repetition via phoneme awareness from age 4 to 6 (consistent with the 'orthographic restructuring' hypothesis, Ziegler et al., 2003, 2004), and a direct influence from age 4-5 while reading also had a direct influence from age 6-9 (consistent with the view that orthographic cues assist in memory for new words). Our work has implications beyond the field of phonological processing, highlighting the importance of literacy acquisition as stimulating domain-general changes in cognitive skills (e.g. in visual processing, Duñabeitia, Orihuela, & Carreiras, 2014).

Verbal short-term memory is critical when learning a serial decoding strategy

Our study is the first to demonstrate a direct contribution of VSTM that is specific to the early stages of reading, when children are learning to read words by translating individual letters into sounds and then blending them to pronounce the word (e.g., 'b-a-t'). This finding particularly aligns with the ideas of Martinex-Perez et al. (2012) that it is the serial-order component of short-term memory, not the item component that is most relevant to decoding. Our VSTM tasks (repetition of digits and phonemes) loaded most heavily on serial order memory as the items involved existing, well-specified phonological representations. In contrast, nonword repetition loaded most strongly on item memory as the items required the creation of new phonological representations (involving a new 'frame'; Gathercole et al., 1991). Therefore, it stands to reason that there woud be a unique contribution of our VSTM factor to reading. This happened during the first two years of school as it is a time when children mostly use decoding strategies to read. Decoding is the strategy prioritized in synthetic phonics teaching, and places demands on serial order memory in order to organize and retain letter sounds in the appropriate sequence. As children progress beyond their second year at school, they begin to build up their sight word vocabulary (Ehri, 2017), and rely less on a decoding strategy, thus reducing the load on serial order memory. This suggests that once children have grasped the basics of serial decoding, there is no longer an independent causal influence of serial order memory on reading.

Phononological memory indirectly predicts reading via phoneme awareness

Across the 5 years of the study (age 4-9), we found that both VSTM and nonword repetition predicted reading indirectly over time, via phoneme awareness (from age 4-5-6, and from age 5-6-9) . These relationships support the existence of the longitudinal mediated pathway proposed in the Introduction. In step one, good phonological memory skills facilitate encoding of increasingly complex verbal stimuli, which stimulates the development of increasingly fine-grained phonemic representations (consistent with Gathercole et al., 1991). In step two, fine-grained phonemic representations support the development of decoding skills (see Hulme & Snowling, 2013 for a review). We find that these relationships apply from early to intermediate reading development.

Dynamic consequences of reading on nonword repetition

In considering potential advantages of reading on the development of phonological memory, our findings highlight important differences between VSTM (as measured by tasks tapping into serial order) and nonword repetition. Reading significantly influenced the development of nonword repetition, but did not contribute to the development of VSTM (which was remarkably stable over time), either directly or indirectly. On the other hand, there was a significant influence of reading on nonword repetition that changed over time. There was an indirect relationship from letter-knowledge to nonword repetition via phoneme awareness from age 4-5-6, and a direct link from age 4-5, and finally, a direct relationship from word-reading to nonword repetition from age 6 to 9. Our findings build on those of Nation and Hulme (2011) by demonstrating that the relationship between reading and nonword repetition is partly mediated by the development of phoneme awareness over the first two years of school.

The significant relationships observed from letter-knowledge to phoneme awareness between age 4 and 5 and from reading to phoneme awareness between age 6 and 9 support the theory outlined in the Introduction: that learning to read promotes an 'orthographic restructuring' of phonological representations (in line with the theory of Ziegler and colleagues, 2003, 2004). Namely, as children learn the mappings between letters and sounds, words that are similar in both sound and spelling become more finely specified to reflect this phoneme-level knowledge. Further work is needed to examine the mechanisms behind orthographic restructuring. For example, is the degree to which phonological forms are restructured dependent on the consistency of the words that children learn to read/spell? The absence of such a relationship between age 5 and 6 was potentially due to the longitudinal stability of reading and phoneme awareness between age 5 and 6. Further study is needed to see if and why this crucial link does not apply during the second year of school.

The direct influences of reading on nonword repetition suggest that children's proficiency in reading enables them to use orthographic information to solve phonological processing tasks (consistent with Castles & Coltheart, 2004). These relationships were subject to developmental change. The link from letter knowledge at age 4 to nonword repetition at age 5 suggests that children were using basic orthographic knowledge (single letters) to help them encode and repeat nonwords. At age 5, children were mainly repeating single syllable nonwords, and visualising one or more letters would be an effective strategy (e.g., if you know the first 1-2 letters, the rest of the word is easier to predict). On the other hand, the direct influence of reading on nonword repetition from age 6 to 9 suggests a different mechanism. Here, children were repeating complex multisyllabic words and it is probable that these more advanced readers were able to enhance their nonword repetition performance by additionally using orthographic cues. Namely, if you know the spelling of the nonword, it will be easier to remember.

Althogether, these direct and indirect relationships from reading to nonword repetition are consistent with the view that reading expertise supports lexical quality (indexed by stable, context-free mental representations of words, containing phonological, orthographic and semantic information, tightly bound together, Nation, 2017; Perfetti, 2007). As the links between orthography and phonology become tighter, this leads to higher quality, better specified lexical representations, which improves encoding of these representations in item memory (Demoulin & Kolinsky, 2015). Such item-level encoding is clearly more important for nonword repetition than for digit span and phoneme repetition, where the items already exist as established representations. This may be why we did not observe significant links between reading/phoneme awareness and the development of VSTM at any time point.

Practical implications and future work

Our findings will help researchers and educators to understand the cognitive skills that underlie reading development, and to be aware of the consequences of learning to read on those same skills. Our participants were taught to read using synthetic phonics, which focuses on translating each grapheme into phonemes, then blending these sounds together to pronounce the word (as recommended by Rose, 2006). As expected for a phonics-educated sample, we find a strong role of phoneme awareness on reading (e.g., Shapiro & Solity, 2016). However, over and above the role of phoneme awareness, we have additionally demonstrated that phonological memory (measured by tasks tapping serial order) is critical for reading in the first two years of school. This finding may be explained in part by the focus on phonics instruction. Specifically, children who are good at accurately reproducing an ordered sequence of sounds will be more likely to quickly grasp the skill of decoding. It is important that teachers are aware that although decoding depends fundamentally on phoneme awareness and letter-sound knowledge, there are other skills involved, and some children may struggle with the memory demands of the task.

Our longitudinal findings, although compelling, are correlational in nature and therefore cannot directly evidence causal connections. Nevertheless, in combination with intervention research, they can provide support for causality (Hulme, 2018). The indirect links we find between phonological memory and reading, via phoneme awareness, align with research showing a causal link between phonemic representations and reading (as evidenced by positive effecs of phoneme awareness training on reading, e.g. Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012). Yet, they do not motivate interventions to train phonological memory directly, (consistent with evidence that training children in the repetition of items does not transfer to other skills, Melby-Lervåg & Hulme, 2013). Although, the direct link between serial order memory and reading in the first two years suggests that a time-limited intervention may be effective in beginning readers. However, the strong longitudinal stability of serial order memory suggests that children may be resistant to training (consistent with Shipstead, Redick, & Engrie, 2010).

This high longitudinal stability of VSTM was similar to that found in previous work (e.g. Wagner et al., 1994, 1997), as was the medium-high stability of reading and PA (Peterson et al., 2017, Wagner et al., 1997). Nevertheless, it is noteworthy that the over-time stability of nonword repetition was lower than for our other constructs. This fits with well-established theories of speech production. It is well-known that the developmental period we studied covers a critical time in terms of acquiring the pronunciation of certain consonant clusters (McLeod, Van Doorn & Reed, 2001). Since children acquire these phonemes at different rates, we would expect a discrepancy in some children's performance on the same items over time. In addition, a significant minority of infants are classified as 'late talkers' (Rescorla, 2011), which can lead to poor longitudinal stability of language ability in large unselected samples of children between infancy and school age (5-8 years, as found in Duff et al., 2015). Therefore the resolving 'late talkers' in our study will have reduced the average stability of nonword repetition across the whole sample. Consistent with this, the raw correlations we found between nonword repetition were similar to those reported by Melby-Lervåg et al., (2012b) in another large-scale study covering the same developmental period.

Another important implication of our work relates to the influence of reading on linguistic skills. In particular, we found that reading has knock on effects on children's developing nonword repetition ability. This means that we may expect to see deficits in this skill over time in reading-impaired children and adults (as suggested by Catts, Adlof, Hogan & Weismer, 2005; Melby-Lervåg & Lervåg, 2012). And more positively, that interventions that improve reading from the intermediate stages upwards may benefit nonword repetition. The ability to create detailed and precise phonological representations is key to accurately encoding, remembering and producing new words (e.g., when learning new scientific terms; refraction vs. reflection). Therefore, being able to encode and remember new words that are presented orally (as indexed by nonword repetition ability) provides a huge educational advantage.

Being literate gives you more than just the ability to decode single words, and reading experience is likely to be key to the development of rich, high quality lexical representations comprising meaning, orthographic and phonological information (Nation, 2017). Related to this, there is debate as to whether oral encoding helps in learning the meaning of new words; e.g., Gathercole & Baddeley (1993) found significant links between nonword repetition and vocabulary, while Melby- Lervåg et al., (2012b) found no significant relationship. A longer-term investigation of growth in reading skill, reading experience and vocabulary is necessary to better understand the benefits of literacy for oral language more generally.

Conclusion

The present study has uncovered changes in the relationship between phonological memory and reading as children move from being non-readers to proficient readers during their first five years of school. Our longitudinal structural equation models revealed that different aspects of phonological memory (serial order memory versus nonword repetition) show different relationships with reading over time. We found that tasks that tapped into serial order memory had a direct independent influence on reading during the first two years of school, demonstrating that children need to be able to store and produce sounds in the correct order in order to grasp basic decoding skills.

Perhaps our most important finding was the dynamic influence of reading on nonword repetition. We found a longitudinal influence of reading on nonword repetition, both indirectly via phoneme awareness, and directly. This is consistent with the view that reading promotes the development of tighter links between orthography and phonology (orthographic restructuring), leading to higher quality, better specified lexical representations. In addition, direct links between reading and nonword repetition suggest that having better reading skills enables children to explicitly use orthographic knowledge to represent unfamiliar items in memory (i.e., imagining the visual form of a word). We have recently made significant advances in understanding how to teach reading (see Castles et al., 2018 for a review). As more children worldwide benefit from quality reading instruction, we predict this will have knock on effects beyond literacy, influencing children’s broader language capabilities.

The data that support the findings of this study are openly available in the UK Data Archive at http://reshare.ukdataservice.ac.uk/852671/, reference number 10.5255/UKDA-SN-852671

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Table 1

Descriptives and internal consistency reliability of the measures

Variable	Max	Age 4 Time 1 M (SD)	Skew	Age 5 Time 2 M (SD)	Skew	Age 6 Time 3 M (SD)	Skew	Age 9 Time 4 M (SD)	Skew	Cronbach's alpha
Reading										
Letter-sound knowledge: singles	25	12.23 (8.11)	-0.12	22.64 (3.25)	-3.11	-	-	-	-	.74 (T1)
BAS word reading	90	2.01 (5.36)	5.66	13.10 (12.28)	1.58	36.99 (17.03)	-0.09	66.75 (11.15)	-1.39	.99^b
DTWRP reading	90	2.47 (5.48)	5.67	14.63 (13.20)	1.91	39.98 (19.89)	0.05	71.76 (12.51)	-1.46	.97^b
Phonological memory										
Digit span: total correct	40	12.71 (3.98)	-0.25	14.69 (3.92)	-0.10	16.87 (3.72)	-0.03	19.97 (3.60)	-0.43	.85
Digit span	8	3.28 (0.86)	-0.71	3.67 (0.88)	0.14	4.23 (0.78)	-0.08	4.84 (0.74)	-0.46	.87^b
Phoneme repetition	21	6.43 (3.45)	0.21	8.58 (3.47)	-0.10	10.82 (3.29)	-0.39	-	-	.71
Nonword repetition: Set1	9	4.03 (2.03)	0.10	5.41 (2.01)	-0.52	6.04 (1.61)	-0.74	-	-	.84
Nonword repetition: Set2	12	3.79 (2.14)	0.23	5.58 (2.39)	-0.12	6.52 (2.43)	-0.34	-	-	
Nonword repetition: simple	24		-	-	-	-	-	18.05 (3.42)	-0.42	.84 (T4)
Nonword repetition: complex	24	-	-	-	-	-	-	12.49 (7.27)	-0.11	
Phoneme awareness										
Phoneme isolation	21	3.66 (3.75)	1.03	8.55 (4.63)	0.22	12.80 (4.42)	-0.79	-	-	.93
Phoneme deletion	21	0.50 (1.43)	4.03	2.06 (3.23)	1.93	5.95 (4.66)	0.52	-	-	.90
PhAB deletion	18	-	-	-	-	-	-	14.09 (4.21)	-1.49	.93^b (T4)

Note: Cronbach's alphas are sample-specific at T2 unless otherwise specified. ^{b} is published reliability at age 5-6. Phoneme repetition, nonword repetition, phoneme isolation and deletion T1-T3 are from the CPSAS. Nonword repetition T4 is from the TOPhS. BAS = British Ability Scales, DTWRP = Diagnostic test of word reading processes. PhAB = Phonological assessment battery. Light grey = measures administered but not analysed due to developmentally appropriate floor/ceiling effects.

Table 2

Estimated correlations between latent variables over time

	Age 4	Age 5	Age 6	Age 9
Word- reading				
Age 4 (LK)	-	.59	.58	.41
Age 5		-	.79	.59
Age 6			-	.77
Age 9				-
Phoneme awareness				
Age 4	-	.59	.48	.28
Age 5		-	.61	.43
Age 6			-	.51
Age 9				-
VSTM				
Age 4	-	.98	.91	.78
Age 5		-	.98	.79
Age 6			-	.81
Age 9				-
Nonword repetition				
Age 4	-	.51	.31	.43[1]
Age 5		-	.58	.32
Age 6			-	.30
Age 9				-

Note: Correlations are Bivariate (Pearson's *r*). All correlations significant at $p < .05$. [1] Estimated without missing data (model would not converge when all missing data included).

Appendix A

Procedure and items for non-standardised phonological memory tasks

Phoneme repetition (CPSAS)

You are going to hear some letter-sounds. I'd like you repeat them back in the order that you hear them.

Part 1 (2-phon)	Part 2 (3-phon)	Part 3 (4 phon)
p, k	p, k, g	k, g, k, p
k, p	p, g, k	p, k, g, k
g, k	k, g, p	g, k, p, g
k, k,	g, k, p	k, p, k, g
k, g	g, p, k	g, k, g, p
p, k	k, p, k	k, p, k, g
k, g		
p, k		
k, p		

Nonword repetition (CPSAS)

You will hear some funny sounding words. I want you to say each word back to me exactly how you hear it.

Set 1	Set 2
bem	fass
mig	besk
feep	doost
swib	thickery
brug	ballop
drick	glistow
zind	dopelate
pag	sepretenial
baff	underbrantuand
	perplisteronk
	loddernapish
	versatrationist

Nonword repetition (TOPHS)

You will hear some funny sounding words. I want you to say each word back to me exactly how you hear it.

Simple nonwords		Complex nonwords	
Simple short	Simple long	Complex short	Complex long
depe	bedepa	dremp	dremperi
pifi	difipl	frimp	frimpele
kete	sipifi	prilf	prilfite
dep	feketa	klest	klestele
fip	deperi	bedremp	bedemperi
pif	fipela	difrimp	difimpele
dempe	pifite	siprilf	fekestele
fimpl	ketele	feklest	difripele
keste	bedeperi	bedemp	siprifite
fimp	difipele	difimp	fekletele
pilf	sipifite	siprif	bedremperi
kest	feketele	feklet	siprilfite

Appendix B

Correlations between indicator variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Age 4 (Time 1)																											
1. Letter-sound knowledge	-	.31	.39	.20	.14	.57	.58	.54	.36	.34	.17	.32	.47	.56	.54	.33	.26	.10	.25	.37	.41	.37	.28	.25	.22	.27	.23
2. Phoneme repetition		-	.46	.24	.20	.42	.40	.43	.50	.47	.15	.30	.35	.35	.36	.37	.33	*.07*	.16	.27	.28	.27	.32	.36	.34	.36	.22
3. Digit span: total correct			-	.16	.21	.41	.38	.37	.47	.71	.21	.31	.36	.40	.41	.37	.65	.16	.25	.37	.35	.34	.51	.57	.32	.36	.23
4. Nonword repetition Set 1				-	.35	.30	.15	.15	.24	.11	.26	.18	.23	.07	.09	.10	.10	.10	.11	.22	.07	.10	.15	.10	*.06*	*.11*	.11
5. Nonword repetition Set 2					-	.24	.17	.16	.19	.21	.10	.20	.14	*.13*	.13	.11	.16	.14	*.10*	.14	*.04*	*.05*	*.10*	*.11*	*.07*	*-.06*	*.06*
6. Phoneme isolation						-	.55	.57	.42	.41	.18	.30	.51	.51	.51	.33	.33	.21	.30	.42	.41	.37	.34	.32	.29	.37	.26
Age 5 (Time 2)																											
7. BAS word reading							-	.94	.46	.40	.13	.29	.56	.77	.74	.39	.33	.09	.27	.37	.56	.51	.33	.30	.32	.38	.29
8. DTWRP reading								-	.48	.41	.16	.30	.56	.74	.72	.39	.34	.09	.27	.37	.53	.48	.33	.30	.33	.37	.30
9. Phoneme repetition									-	.51	.23	.30	.46	.44	.45	.51	.46	.18	.25	.38	.37	.35	.37	.34	.35	.36	.24
10. Digit span: total correct										-	.15	.29	.40	.43	.45	.44	.70	.14	.30	.39	.41	.40	.59	.61	.35	.38	.27
11. Nonword repetition Set 1											-	.33	.34	.16	.16	.08	.11	.23	.16	.18	.15	.18	.10	.12	.18	.20	.16
12. Nonword repetition Set 2												-	.33	.32	.33	.29	.29	.13	.29	.29	.25	.23	.21	.17	.17	*.12*	.15
13. Phoneme isolation													-	.58	.59	.38	.37	.19	.34	.50	.48	.45	.31	.29	.39	.42	.33
Age 6 (Time 3)																											
14. BAS word reading														-	.95	.43	.40	.15	.31	.52	.74	.68	.35	.34	.45	.53	.42
15. DTWRP reading															-	.44	.42	.14	.33	.51	.74	.69	.36	.36	.47	.56	.42
16. Phoneme repetition																-	.43	.18	.28	.37	.39	.39	.36	.35	.35	.38	.25
17. Digit span: total correct																	-	.09	.21	.36	.36	.37	.57	.58	.43	.41	.31
18. Nonword repetition Set 1																		-	.33	.34	.13	.13	*.08*	*.08*	.23	.23	*.07*
19. Nonword repetition Set 2																			-	.39	.23	.18	.21	.16	*.08*	*.06*	.11
20. Phoneme isolation																				-	.51	.49	.29	.33	.37	.40	.39
Age 9 (Time 4)																											
21. BAS word reading																					-	.91	.31	.31	.52	.57	.55
22. DTWRP reading																						-	.33	.34	.55	.60	.59
23. Digit span: odds																							-	.72	.31	.33	.22
24. Digit span: evens																								-	.32	.35	.21
25. Nonword repetition Simple																									-	.84	.32
26. Nonword repetition Complex																										-	.35
27. PhAB deletion																											-

Note: Correlations are Bivariate (Pearson's r). All correlations significant at $p < .05$, unless in italics

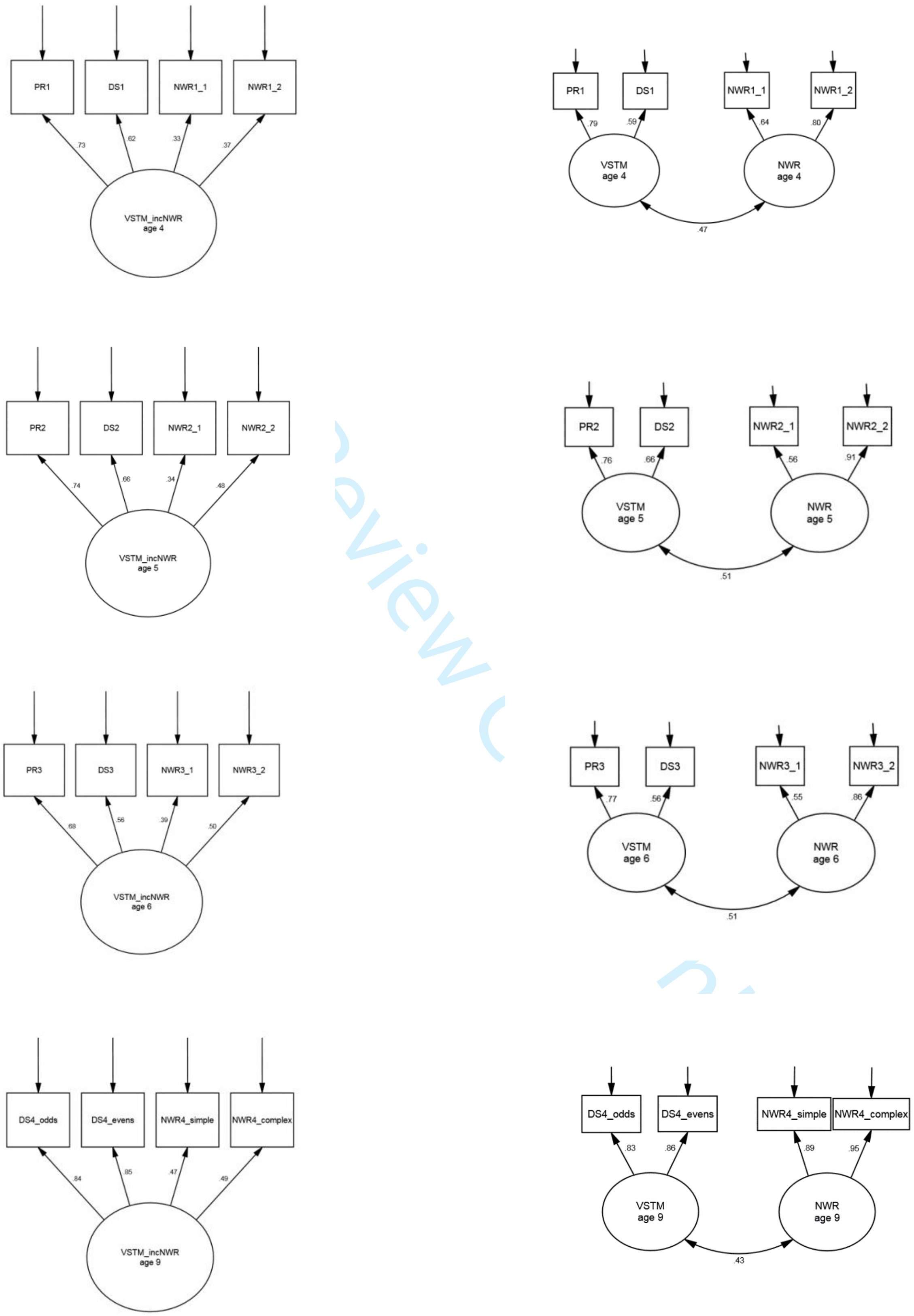
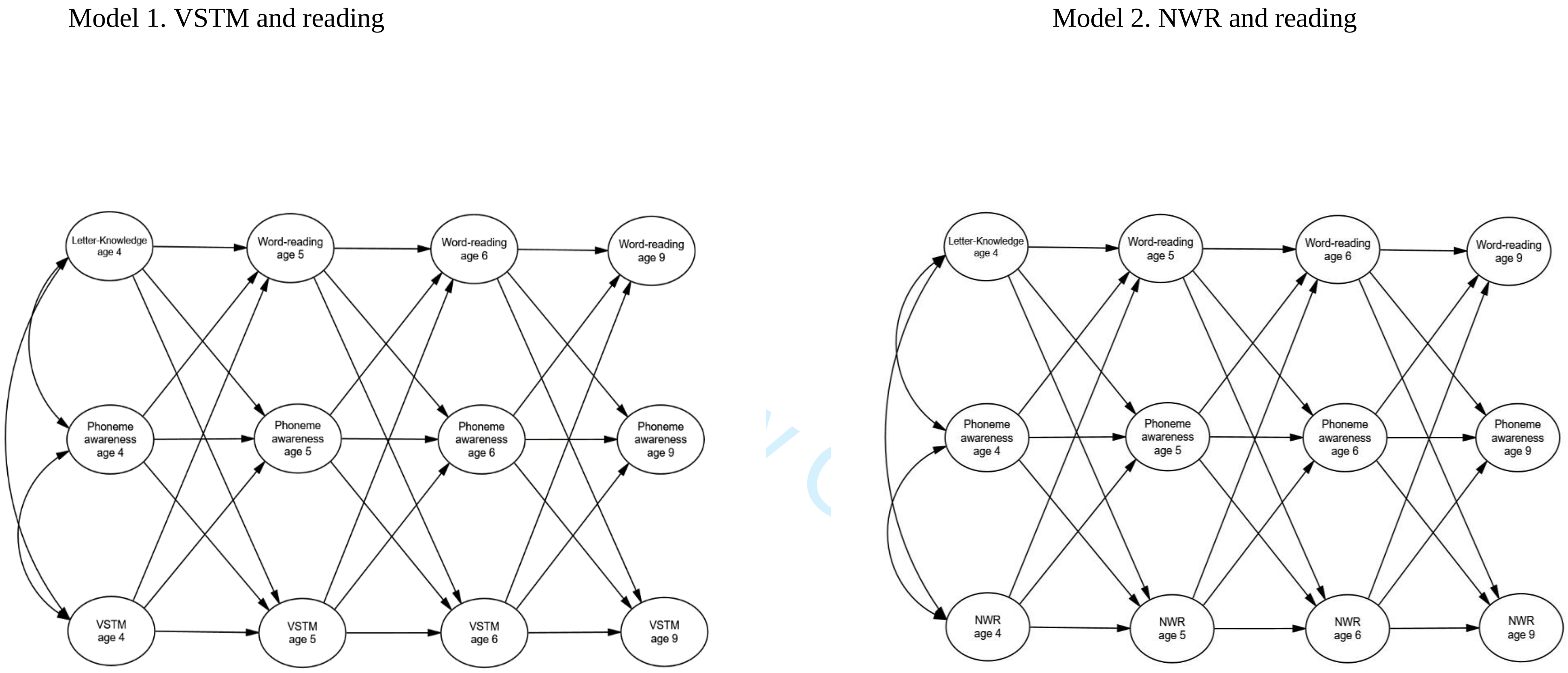


Figure 1. Confirmatory factor analyses for phonological memory one- and two- factor solutions T1-T4. Factor loadings are given next to each link from latent variable to indicator variable. Numbers after each indicator name indicate time point. VSTM_incNWR = Verbal short-term memory including nonword repetition. PR = Phoneme repetition, DS = Digit span total correct, NWR_1= Nonword repetition Set 1, NWR_2 = Nonword repetition Set 2. DS_odds = Digit span total correct odd items, DS_evens = Digit span total correct even items, NWR_simple = Nonword repetition simple items, NWR_complex = Nonword repetition complex items.



Model 1. VSTM and reading

Model 2. NWR and reading

Figure 2. Hypothesised longitudinal models. VSTM = verbal short-term memory, NWR = Nonword repetition

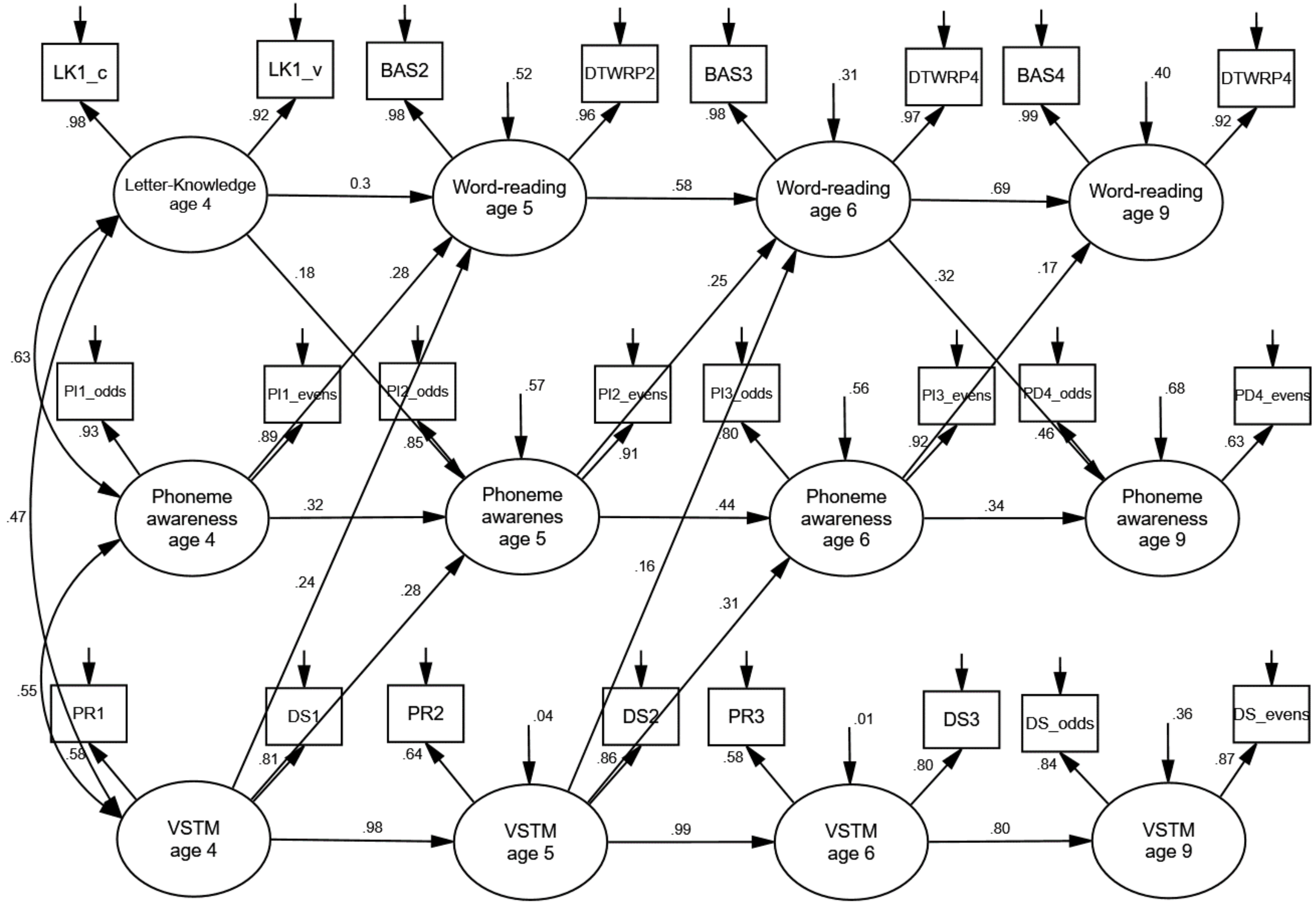


Figure 3. Model 3: Longitudinal relationships between verbal short-term memory and reading. Standardised regression weights are given next to each link between latent variables. All regression weights are significant at the $p < .01$ level. Numbers after each indicator name indicate time point. Residuals (1 -Multiple squared correlation (r^2)) are given above the short arrows feeding into the latent variables. LK_c = letter-sound knowledge: consonants, LK_v = letter-sound knowledge: vowels, BAS = British Ability scales word reading, DTWRP = Diagnostic test of word reading processes, PI_odds = phoneme isolation total correct for odd items, PI_evens = phoneme isolation total correct for even items, PD_odds = phoneme deletion (Phab) total correct for odd items, PD_evens = phoneme deletion (Phab) total correct even items.

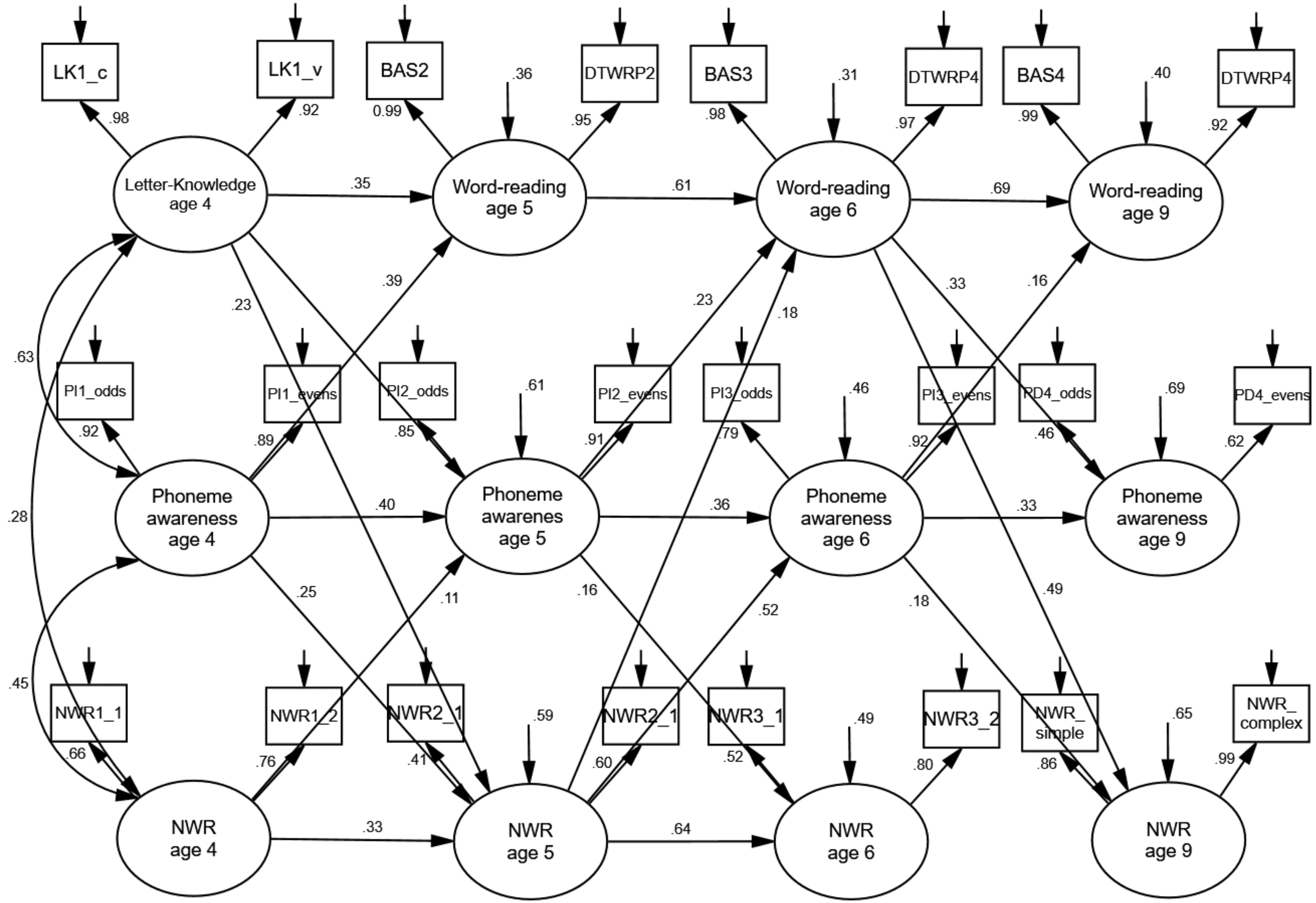


Figure 4. Model 4: Longitudinal relationships between nonword repetition and reading. Standardised regression weights are given next to each link between latent variables. Numbers after each indicator name indicate time point. Residuals (1 -Multiple squared correlation (r^{2s})) are given above the short arrows feeding into the latent variables. All regression weights are significant at the $p < .01$ level except NWR age 4 to phoneme awarenss age 5, $p = .029$, and phoneme awareness age 5 to NWR age 6, $p = .022$. NWR2_1 = nonword repetition T2 Set1 (7 items), NWR3_1 = nonword repetition T3 Set 1 (7 items).

Supplementary information

Table S1

Fit statistics for Confirmatory factor analyses

	χ^2	*df*	*p*	NFI	IFI	CFI	RMSEA	$\Delta\chi^2$	Δdf	*p*
Factor models at T1										
1 factor model	50.48	2	<.001	.842	.847	.843	.176			
2 factor model	1.13	1	.29	.996	1.000	1.000	.01	49.35	1	<.001
Factor models at T2										
1 factor model	69.21	2	<.001	.839	.843	.840	.21			
2 factor model	2.29	1	.13	.995	.997	.997	.04	66.92	1	<.001
Factor models at T3										
1 factor model	67.59	2	<.001	.792	.797	.792	.21			
2 factor model	0.57	1	.45	.998	1.00	1.00	.00	67.02	1	<.001
Factor models at T4										
1 factor model	241.74	2	<.001	.631	.633	.628	.39			
2 factor model	0.10	1	.75	1.00	1.00	1.00	.00	241.64	1	<.001