


A Longitudinal Study of Early Reading Development: Letter-Sound Knowledge, Phoneme Awareness and RAN, but Not Letter-Sound Integration, Predict Variations in Reading Development

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ABSTRACT

It is now widely accepted that phonological language skills are a critical foundation for learning to read (decode). This longitudinal study investigated the predictive relationship between a range of key phonological language skills and early reading development in a sample of 191 children in their first year at school. The study also explored the theory that a failure to establish automatic associations between letters and speech sounds is a proximal causal risk factor for difficulties in learning to read. Our findings show that automatic letter-sound associations are established early, but do not predict variations in reading development. In contrast, phoneme awareness, letter-sound knowledge and alphanumeric RAN were all strong independent predictors of reading development. In addition, both phoneme awareness and RAN displayed a reciprocal relationship with reading, such that the growth of reading predicted improvements in these skills.

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Introduction

Fluent reading skills are a critical foundation for educational success, but many children experience problems in learning to read. Developmental dyslexia, a disorder characterized by impaired word reading and spelling, is estimated to affect between 3 to 8% of the population (Peterson & Pennington, 2015), but this diagnosis represents the lower end of a continuous distribution of reading and spelling skills (Fletcher, 2009). It is, therefore, critically important to determine the cognitive skills that predict variations in reading development, to allow us to identify and treat children at risk of reading difficulties.

Learning to read depends on mastery of the alphabetic principle: that written letters represent the sounds of speech (Byrne & Fielding-Barnsley, 1989, 1990). It proceeds in stages from early visually driven associations between printed letters and word pronunciations to later more sophisticated use of phonological information to drive efficient word recognition processes (Hulme & Snowling, 2009). There is a growing consensus that early reading development is dependent on phonological skills (Fletcher, 2009; Hulme & Snowling, 2013) and that deficits in these skills are probably causally related to difficulties in learning to read. Following on from this, a subset of phonological language skills – phoneme awareness, letter-sound knowledge and rapid automatized naming, have been identified as strong and independent predictors of variations in reading skill (Hulme & Snowling, 2014).

Another recent theory has suggested that dyslexia reflects a failure to automatize associations between speech sounds and letters (e.g. Blomert, 2011; Blomert & Froyen, 2010; van Atteveldt &

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Ansari, 2014). Proponents of this theory suggest that the phonological deficit in dyslexia is a secondary consequence of problems in learning to read, whereas a deficit in forming automatic associations between letters and phonemes is a proximal cause. This theory might be seen as an extension of the view that letter-sound knowledge is critical for early reading development (Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012; Melby-Lervåg, Lyster, & Hulme, 2012). However, the automatic letter-sound integration hypothesis is more specific. According to this view letter-sound associations have to be learned to the point of being automatized in order to support the development of accurate and fluent word recognition skills.

Most studies that support this hypothesis are concurrent ERP or fMRI studies comparing letter-sound processing in small groups of children or adults with dyslexia, to typically developing readers matched for age (Bakos, Landerl, Bartling, Schulte-Körne, & Moll, 2017; Blau et al., 2010; Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Jones, Kuipers, & Thierry, 2016; Karipidis et al., 2017; Kronschnabel, Brem, Maurer, & Brandeis, 2014; Moll, Hasko, Groth, Bartling, & Schulte-Körne, 2016). These studies report atypical (or developmentally delayed) associations between letters and speech-sounds in children with dyslexia, but with little agreement between different studies. In the original ERP studies, typical readers demonstrated an early mismatch-negativity (MMN) in response to mismatched letters and speech-sound pairs, which was absent in adults and children with dyslexia (Froyen, Bonte, van Atteveldt, & Blomert, 2009; Froyen, Willems, & Blomert, 2011). The absence of an early MMN in those with dyslexia has been interpreted as reflecting a deficit in letter-sound integration that is causally related to reading difficulties, however a subsequent attempt to replicate these findings suggests the early MMN is absent only in the most severely impaired dyslexic readers (Žarić et al., 2014).

Similarly, fMRI studies have reported a deficit in letter-sound integration in adults and children with dyslexia; specifically a failure to suppress activation in response to mismatched letter-sound pairs relative to typical age-matched control groups (Blau et al., 2009, 2010). However, such group differences could simply be attributed to group differences in phonological processing, which are not controlled for in these studies (Peterson & Pennington, 2015). Crucially, subsequent studies that have controlled for differences in phonological skills find little evidence of a relationship between letter-sound integration and reading (Clayton & Hulme, 2018; Law et al., 2018; Nash et al., 2017). Studies using a priming task to assess letter-sound integration found that children with dyslexia were significantly faster to respond to a speech-sound when primed by a matching visually presented letter, indicating intact automatic activation of sounds by letters (Clayton & Hulme, 2018; Nash et al., 2017). Both age-matched and reading-age-matched controls showed comparable performance, and across a large unselected group of typical readers, the extent of letter-sound integration did not predict concurrent variance in reading performance. Together, these studies suggest that automatic associations between letters and speech-sounds emerge within the first few years of reading development, but at present there is little evidence that individual differences in letter-sound integration predicts reading above and beyond phonological skills.

In contrast, there is good evidence that phoneme awareness, letter-sound knowledge and RAN are independent predictors of variation in reading skill which may be causally related to difficulty in learning to read (Hulme, Muter, & Snowling, 1998; Hulme, Nash, Gooch, Lervåg, & Snowling, 2015; Landerl et al., 2018; Lervåg & Hulme, 2009; Melby-Lervåg et al., 2012; Muter, Hulme, Snowling, & Stevenson, 2004; Roth, Speece, & Cooper, 2002; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004). The strongest evidence for a causal relationship between both phoneme awareness and letter-sound knowledge and reading development comes from randomized controlled trials (e.g., Bowyer-Crane et al., 2008; Hatcher et al., 2006; Hatcher, Hulme, & Snowling, 2004; Torgesen et al., 1999, 2001). Early, intensive instruction in phoneme awareness and letter-knowledge and the linkages between the two improve children's word reading skills. Furthermore, improvements in reading skills brought about by training letter-sound knowledge and phoneme awareness are mediated by improvements in these skills (Hulme et al., 2012).

Rapid automatized naming (RAN) measures the ability to name a random sequence of objects, colours, letters or digits as quickly as possible. It has been suggested that RAN taps brain areas involved in object recognition and naming that are recruited for learning to read (Lervåg & Hulme, 2009), however there are other competing theories regarding the underlying mechanism driving the RAN-reading relationship (e.g. Jones, Ashby, & Branigan, 2013; Protopapas, Altani, & Georgiou, 2013). RAN can be divided into alphanumeric RAN (letters and digits), and non-alphanumeric RAN (objects and colours). Both concurrent and longitudinal studies show that RAN is a correlate of reading skills (Allor, 2002; Bowey, 2005; Kirby, Georgiou, Martinussen, & Parrila, 2010; Wolff, 2014; for a meta-analysis, see Araújo, Reis, Petersson, & Faisca, 2015). The finding that RAN predicts reading speed in typically developing children and in children with dyslexia, even with non-alphanumeric subtests, shows that this effect is not simply a result of differences in letter or digit knowledge (Lervåg & Hulme, 2009; Verhagen, Aarnoutse, & Van Leeuwe, 2008; Wolf & Bowers, 1999; Wolff, 2014).

In addition to evidence that these three phonological language skills may be causally related to variations in learning to read, there is also mounting evidence that the relationships they share with reading may be bi-directional. Phoneme awareness, in particular, has been found to share a reciprocal relationship with reading, such that learning to read leads to subsequent improvements in phonemic skills (Castles & Coltheart, 2004; Hulme, Snowling, Caravolas, & Carroll, 2005; Perfetti, Beck, Bell, & Hughes, 1987). For example, Perfetti et al. (1987) found a reciprocal relationship between several tests of phoneme awareness and early reading development in 1st graders, with a phoneme deletion test exhibiting the most marked reciprocal relationship. The authors suggested that while a level of phoneme awareness was necessary in order to begin the process of learning to read, more advanced phonemic awareness develops in tandem with the development of reading. Indeed, evidence suggests a possible virtuous circle of reciprocal relationships between phoneme awareness, letter-sound knowledge and reading (Muter et al., 2004), with increased phonemic awareness improving the learning of letter-sound correspondences (Fox & Routh, 1984; Treiman & Baron, 1983), in turn leading to improvements in reading which then drives further refinements of phonemic and letter-sound knowledge.

The extent to which RAN and reading skill may share a reciprocal relationship appears less clear-cut. This may be due to differences in the age of participants and the types of RAN measure used across studies. For example, Compton (2003) reported a reciprocal relationship between RAN digits and word, but not non-word, reading in a representative sample of 1st graders, that was most marked in the poorest decoders. A reciprocal relationship between RAN and word reading speed was also reported in a training study of older Swedish children with reading difficulties (Wolff, 2014). However, in a large representative sample of Norwegian children followed from school entry to grade 4 (Lervåg & Hulme, 2009), alphanumeric RAN predicted the development of word reading fluency but not vice versa. The same pattern was found in a longitudinal study of Dutch children in 1st and 2nd grade, using a composite measure of alphanumeric and non-alphanumeric RAN (Verhagen et al., 2008). Most studies showing reciprocal relationships between the development of reading and RAN have used alphanumeric RAN tasks either early in reading development (when letter and number name knowledge are not expected to be fully automatized) (Compton, 2003; Peterson et al., 2017), or in samples of children with reading difficulties (Wolff, 2014). Thus, it may be that alphanumeric RAN is influenced by reading development only during that phase of development when knowledge of letter and digit names are not yet fully automatized.

In summary, evidence indicates that phonological language skills (letter-sound knowledge, phoneme awareness and RAN) may be causally related to variations in learning to read, while evidence for a relationship between letter-sound integration and reading is far from conclusive. This longitudinal study, therefore, examines the role of letter-sound integration as a predictor of early reading development alongside other better established predictors (phoneme awareness, letter-sound knowledge and RAN). We measure these skills during the first year of school when children are aged 4–5 years old. Theoretically, this is a critical period of development, since it encompasses the first year

of formal reading instruction, when the foundations of children's decoding skills are being established. Measuring children's performance during this period enables us to establish how early automatic associations between letters and speech-sounds emerge. We predict that this early time window of development may be when the automaticity of letter-sound correspondences might make the greatest contribution towards growth in word reading. Furthermore, tracking the development of these foundational skills throughout the first year of school will allow us to investigate potential reciprocal relationships with reading during this critical period of development.

Method

Participants

One hundred and ninety one children (107 male, 84 female) participated in the study. Children were recruited at school entry from 7 primary schools in Greater London. The average age of the children at the start of the study was 4 years, 6 months (range = 4 years, 0 months, to 5 years, 2 months, SD = 3.54 months). Ethical approval was given by the University College London Research Ethics Committee. Head teachers gave written informed consent for children to take part, and the parents of each child were given the option of withdrawing their child from the study before it began.

Design and testing procedure

The children were tested 4 times over a period of 14 months: a) September – December, (Reception Term 1); b) January – March, (Reception Term 2); c) May – July, (Reception Term 3) and d) September – November (Year 1 Term 1). At each time-point children were tested individually in two sessions each lasting approximately 30 minutes. All testing was completed in school. There was a small amount of missing data where children were absent from school. In addition, some children did not complete all tasks at each time-point due to time constraints. However, as tasks were not administered in a fixed order, data can be considered to be missing completely at random (MCAR).

Tests and materials

The children completed an experimental task designed to measure automatic letter-sound integration and a range of measures assessing early reading and language skills.

Letter-sound priming task

This task involved the successive presentation of a visual letter prime and an auditory letter-sound target. Children were required to decide on each trial whether the second stimulus (the “target”) was a speech-sound or a “robot sound”. Fifty percent of trials consisted of speech sounds; the other 50% of trials involved the presentation of a scrambled speech sound (“robot sound”). Response time (RT) was measured to the auditory stimuli (speech/scrambled speech decision RT). [Figure 1](#) details the trial structure across the three experimental conditions.

Stimuli

Stimuli in this task were recordings of the 5 letter-sounds /tə/ (293ms), /də/ (263ms), /və/ (428ms), /zə/ (413ms) and /dʒə/ (357ms). Scrambled versions of these stimuli were created in Matlab by randomly assembling 5ms segments of the original signal (Ellis, 2010). These scrambled sounds were identical in length, energy and spectral composition to the original speech sounds but sounded completely unlike speech. The lowercase letters corresponding to the letter-sounds were used as the letter primes and were presented in Arial font (approximately 23 x 20mm). On 50% of trials a letter prime was presented and on the other 50% of trials one of five novel letter-like forms (adapted from Taylor, Plunkett, & Nation, 2011) was presented.

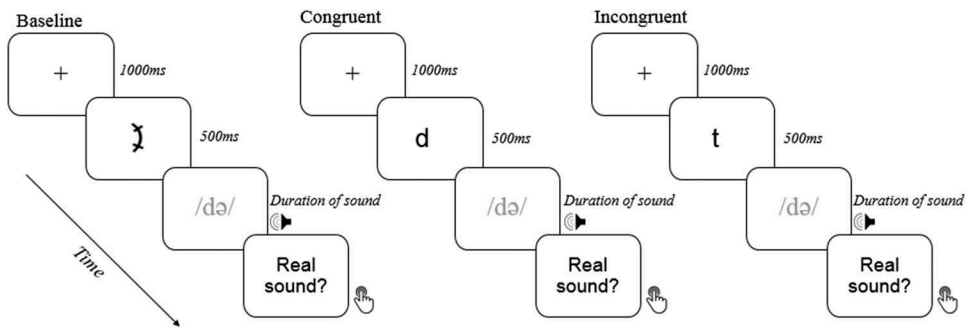


Figure 1. Trial structure for each of the three experimental conditions.

Apparatus

Stimuli were presented and responses recorded (speed and accuracy) using E-Prime Software (version 2.0) using a Psychology Software Tools Serial Response Box (SRB; model 200a) and a laptop running Windows 7. Auditory stimuli were presented through headphones.

Procedure

Children were instructed to attend to both the letter and speech-sound and decide whether the sound was a “real” speech-sound using “yes” and “no” response keys on the response box. Before the task began children were familiarized with the procedure in thirteen practice trials.

On each trial a centrally located fixation point was presented for 1000ms, followed by the letter or non-letter stimulus, presented in black and appearing on a white screen for 500ms. The auditory target was presented over headphones and its onset was synchronous with the offset of the visual letter. Each trial was followed by the visual prompt “Real sound?” Response times from the response box were recorded from the onset of the auditory target. The experimenter monitored the child’s performance, controlling the presentation of trials.

There were six conditions in the letter-sound priming task. In the congruent condition, the prime and target were the same letter/sound. In the incongruent condition the prime and target were not the same letter/sound. In the baseline condition, the prime was a novel letter and the target was a speech-sound. There were three additional control conditions to prevent children detecting the relationship between primes and targets and generating expectancies. In these control conditions the target was a non-speech sound. Novel symbols and scrambled speech-sounds were yoked to create pseudo baseline, congruent and incongruent control conditions.

The letter-sound priming task was completed across two sessions on consecutive days to reduce attentional demands. In total there were 20 congruent and 20 incongruent trials. In the congruent condition there were four trials of each pairing and in the incongruent condition each letter prime was presented once and paired with all other speech-sounds. There were 40 baseline trials to ensure equal probability of the presentation of a novel symbol relative to a real letter prime. This resulted in 180 trials in total, including 20 “catch” trials to ensure children were attending to the screen. On catch trials the same letters were presented in a black and white animal print (for example, zebra stripes) and children were instructed to make a different response (using a different button on the response box).

Letter-sound knowledge

Children completed the letter-sound knowledge (LSK) subtest from the York Assessment of Reading for Comprehension (YARC; Hulme et al., 2009). This test required children to say the sound corresponding to 32 letters and digraphs.

Reading

Children completed the Early Word Recognition (EWR) subtest from the YARC (Hulme et al., 2009). This test required children to read aloud a list of words of increasing difficulty without time pressure. The maximum possible score is 30.

Phoneme awareness

Children completed the sound deletion subtest from the YARC (Hulme et al., 2009). In this test children heard a word (and saw an accompanying picture) and were required to repeat it and then repeat it again after deleting a sound (for example “Can you say seesaw? Can you say it again but this time don’t say saw?”). Practice trials ensured children understood the instructions. There were 17 items of increasing difficulty and the number of items answered correctly was recorded.

Rapid automatised naming (RAN)

Children completed two RAN subtests (colours, and digits) from the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999). Each subtest required children to name two 9×4 arrays of stimuli as quickly and accurately as possible. The time taken to name all of the items was recorded as was the number of errors (incorrect naming and/or omission of an item). Testing was discontinued if the child made four or more errors on the first stimulus array.

Results

Means and standard deviations for all measures at each time-point are shown in Table 1. Measures show a good range of scores, with the exception of EWR and Phoneme deletion, where many children were at floor at Time 1 (T1). As expected, measures of reading, letter knowledge, phoneme deletion and RAN were significantly correlated at each time point. Standardised measures correlated well across time points. Children improved substantially in performance on all phonological tasks over the course of the study, most markedly between T1 and T2. For correlations between all measures across all time points see Appendix 1 in the online supplementary materials.

The emergence of letter-sound priming

Only correct responses were considered and outliers were removed from the raw reaction time (RT) data. RTs over 5000ms were first removed as this was considered to reflect a lapse in attention. A non-recursive outlier removal procedure was then used (Selst & Jolicoeur, 1994). Finally, RT data were excluded from the analysis where response accuracy was below 75% correct. Following these steps, at T1, 85% of the RT data were included in the analyses, at T2, 83% of the RT data were included, at T3, 89% of the RT data were included and at T4, 82% of the RT data were included.

The mean correct response times in each condition, together with 95% within-subject confidence intervals (Morey, 2008) are shown for each time-point in Figure 2. At T2-4 it is clear that there is an identical pattern across conditions, with faster responses in the congruent condition compared to the baseline condition, and no appreciable slowing in the incongruent condition. However, at T1 children show a contrasting pattern, with similar response times in the baseline and congruent condition and slowing in the incongruent condition.

Response times for the baseline, congruent and incongruent conditions for each time point were compared using a mixed effects linear model treating participants and items as crossed random effects.

At T1 there was no significant difference between RTs in the congruent and baseline condition (marginal mean difference = $-7.15 = [95\% \text{ CI } -37.53, 23.22]$, $z = -0.46$, $p = .644$; $d = .03$) but children were significantly slower in the incongruent than baseline condition, (marginal mean difference = $38.33 = [95\% \text{ CI } 8.09, 68.56]$, $z = 2.48$, $p = .013$, $d = .13$).

Table 1. Means, standard deviations and reliabilities for all measures at each testing occasion.

Measure	Time 1			Time 2			Time 3			Time 4		
	Mean age: 55.63 (3.54) months	M (SD)	Reliability	Mean age: 59.20 (3.41) months	M (SD)	Reliability	Mean age: 63.29 (3.51) months	M (SD)	Reliability	Mean age: 66.72 (3.52) months	M (SD)	Reliability
LSK Raw Score	1184	13.47 (8.40)	.85 ^a	1179	24.49 (4.84)	.85 ^a	1187 ^w	27.98 (3.88)	.85 ^a	1179 ^w	27.96 (3.41)	.85 ^a
EWR Raw Score	1180	2.27 (5.11)	.96 ^a	1176	7.95 (6.52)	.96 ^a	1180	14.81 (7.80)	.96 ^a	1176	16.24 (8.47)	.96 ^a
Phoneme Deletion Raw Score	1181	2.70 (2.28)	.85 ^a	1174 ^w	4.23 (2.57)	.85 ^a	1183 ^w	5.95 (3.03)	.85 ^a	1178	6.02 (3.37)	.85 ^a
RAN												
Digits	1121	50.91 (18.83)	.82 ^b /.91 ^t	1142	40.58 (13.39)	.82 ^b /.91 ^t	1174	35.42 (12.40)	.82 ^b /.91 ^t	1167	34.10 (11.63)	.82 ^b /.91 ^t
Colours	1172	64.79 (22.29)	.71 ^b /.78 ^t	1158	59.51 (23.78)	.68 ^b /.78 ^t	1175	52.51 (18.26)	.75 ^b /.78 ^t	1172	51.97 (17.10)	.75 ^b /.78 ^t
LSI Priming task												
Baseline RT	1117	1358.60 (253.04)	.85 ^b	1127	1367.19 (297.84)	.90 ^b	1164	1306.09 (320.91)	.94 ^b	1151	1264.13 (268.56)	.92 ^b
Congruent RT	1117	1349.57 (252.29)	.74 ^b	1127	1305.31 (328.84)	.86 ^b	1164	1240.09 (334.63)	.87 ^b	1151	1223.20 (284.50)	.84 ^b
Incongruent RT	1117	1398.13 (309.06)	.77 ^b	1127	1363.68 (324.74)	.81 ^b	1164	1296.25 (344.46)	.86 ^b	1151	1245.62 (294.60)	.85 ^b

^a reliability is Cronbach's alpha calculated on random sample of 50 children at Time 1; ^b Cronbach's alpha calculated from 4 item parcels at each time point; ^c Cronbach alpha from manual; These values are the correlations between the same variable one time point later; ^t Test-retest reliability for children progressing to Form B; ^w Winsorised mean. LSK – Letter-sound Knowledge; EWR = Early Word Reading; RAN = Rapid Automatised Naming (Form A); LSI = Letter-sound Integration.

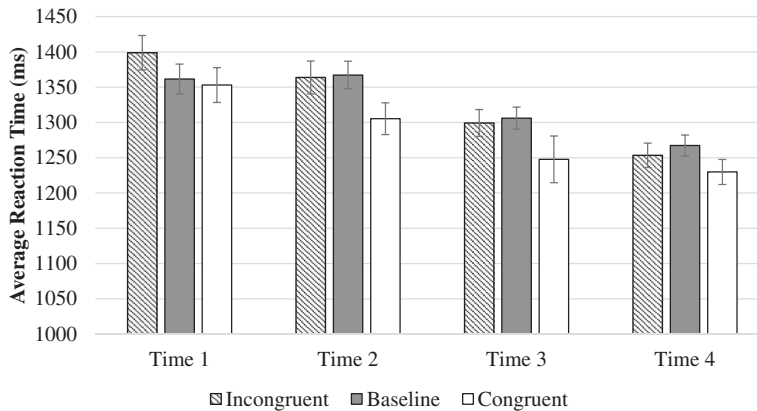


Figure 2. Response times for each condition of the LSI priming task at each time point. Error bars are 95% CIs.

At T2, 3 and 4 RTs in the congruent condition were significantly faster than in the baseline condition (T2, marginal mean difference = -59.30 [95% CI $-86.11, -32.49$], $z = -4.34$, $p = .000$; $d = .20$; T3 marginal mean difference = -55.58 [95% CI $-78.02, -33.14$], $z = -4.86$, $p = .000$; $d = .18$; T4 marginal mean difference = -37.46 [95% CI $-59.80, -15.12$], $z = -3.29$, $p = .001$; $d = .13$) but there was no significant difference between response times in the baseline and incongruent conditions (T2 marginal mean difference = -0.07 [95% CI $-27.03, 26.89$], $z = -0.00$, $p = .996$, $d = .01$; T3 marginal mean difference = -6.82 [95% CI $-29.16, 15.53$], $z = -0.60$, $p = .550$, $d = .02$; T4 marginal mean difference = -12.89 [95% CI $-35.20, 9.41$], $z = -1.13$, $p = .257$, $d = .04$).

The relationship between letter-sound priming and reading related skills

We modelled the development of reading skills using growth curve models. As most children at T1 could not read, we had to restrict the reading growth model to T2, T3 and T4. Furthermore, at T1 there was no statistically significant facilitation effect in the letter-sound integration task, but between T2 and T4 there was a statistically significant facilitation effect (faster reaction times to letter sounds that were preceded by their corresponding printed letter). Because growth was faster between T2 and T3 compared to between T3 and T4, we fitted a nonlinear growth model where we freely estimated the middle time point. This gave us a model with a significant intercept ($m = 7.899$ words, $p < .001$) at T2 (initial status), significant growth ($m = 8.223$ words per year, $p < .001$) and significant variance in both the intercept and rate of growth ($sd = 6.410$, $p < .001$ and $sd = 4.107$, $p = .049$ for intercept and growth, respectively).

First, we wanted to see if our measure of facilitation in the letter-sound integration task was a predictor of initial status and growth in word reading. In order to correct for measurement error in the reaction time measures we created latent variables for both baseline and congruent reaction times by grouping the items into four parcels for each construct, at each time point. These parcels were then used as indicators of a latent baseline reaction time construct and a latent congruent reaction time construct that allowed us to estimate the true score regression of reading growth on facilitation in the letter-sound integration task. We assessed facilitation by taking the residual of congruent reaction times after regressing them on baseline reaction times.

The full model is shown in [Figure 3](#). Here, both baseline reaction time and the residual of congruent reaction time (i.e. facilitation: congruent reaction time that is independent from baseline reaction time) at T2 are used as potential predictors of initial status and growth in word reading (between T2 and T4). As can be seen from [Figure 3](#), shorter baseline reaction times at T2 were associated with better initial status and faster growth in early reading skills.

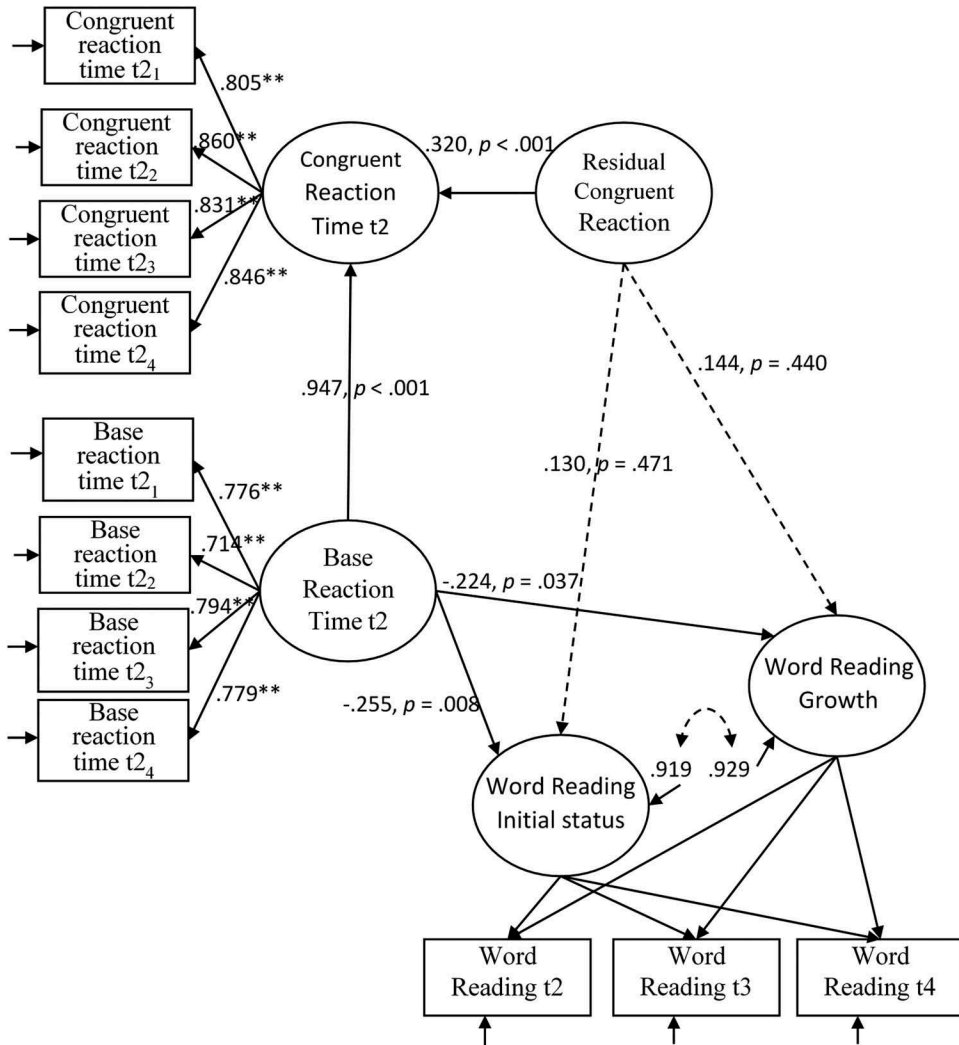


Figure 3. Growth model of relationship between letter-sound integration (measured at T2) and early reading development (assessed at T2, T3, T4). For each reaction time measure there are four item parcels indicated by subscripts 1–4. All coefficients are standardized.

However, baseline reaction time explained 89.70% of the variance in congruent reaction time and the residual of congruent reaction time was not a significant predictor of either initial status (unique $R^2 = .017$) or the rate of growth (slope; unique $R^2 = .020$) in reading skills. This model had a good fit to the data, $\chi^2(39) = 64.351$, $p = .007$, RMSEA = .059 (10% CI = .031–.084), CFI = .980, TIL = .972.

The results of the model in Figure 3 show clearly that the degree of facilitation in the letter sound integration task at T2 (the unique effects of congruent reaction time after accounting for baseline reaction time) plays no appreciable role in predicting individual differences in initial reading levels or rates of growth in reading between T2 and T4. However, in that model baseline RT is a predictor of both initial reading level and the rate of growth in reading. The different measures of RT in the letter-sound integration task were very highly correlated, and in subsequent analyses we proceeded to assess the dimensionality of the RT measures and their possible role as predictors of reading development. It seems quite possible, based on the model in Figure 3, that a measure of overall speed

on the letter-sound integration task (rather than the degree of facilitation on the task) would be a unique predictor of reading development.

To examine the dimensionality of the RT measures from the letter-sound integration task we estimated a confirmatory factor analysis where we included the three measures (baseline, congruent and incongruent) in the same latent variable at each of the four time points. This model had scalar invariance, $\chi^2(12) = 17.453, p = .133$, and a very good model fit, $\chi^2(60) = 83.866, p = .023$, RMSEA = .047 (10% CI = .018-.069), CFI = .984, TIL = .982. As can be seen from Figure 4 the standardised factor loadings were strong for all three reaction time scores at all time points (ranging from .812 to .955). There were strong and significant correlations between this overall RT factor at T2, T3 and T4 but no significant correlations between this factor at T1 and the later time points. This model shows that the three reaction-time scores load very well on a single latent variable that has the same structure at all time points and shows strong stability between T2 and T4. The absence of correlations between T1 and the later time points, presumably reflects children's insecure letter knowledge at T1.

To see if this overall latent RT factor predicted growth in reading we re-estimated the model in Figure 3 but replaced the observed baseline and congruent reaction-time scores with the overall latent reaction-time factor. As Figure 5 shows, the reaction-time factor predicted both the intercept and rate of growth of reading skills; faster reaction times being associated with better initial skills and faster growth in reading. The model had an excellent fit to the data, $\chi^2(8) = 4.569, p = .803$, RMSEA = .000 (10% CI = .000-.055), CFI = 1.00, TIL = .101.

However, when letter knowledge, phoneme awareness and RAN were included as predictors, the overall latent-reaction time factor did not predict any unique variance in either initial status or the growth of reading. In this model (see Figure 6), letter knowledge, phoneme awareness and RAN all predicted unique variance in both the initial status ($R^2 = .664$) and the growth of reading ($R^2 = .373$). RAN was estimated by a latent variable with RAN colours and RAN digits as indicators while letter knowledge and phoneme awareness were estimated by latent variables with only one indicator where the residual was fixed according to their measures' reliabilities ($\alpha = .85$). This model had an excellent fit to the data, $\chi^2(25) = 32.551, p = .143$, RMSEA = .040 (10% CI = .000-.075), CFI = .994, TIL = .89.

The correlations between the latent variables in Figure 6 are shown in Table 2. As might be expected RAN, letter knowledge and phoneme awareness show moderate correlations with each other. Overall reaction time on the letter-sound integration task also shows moderate correlations with RAN, letter knowledge and phoneme deletion (r 's between .33 and .39), this suggests that performance on the letter-sound integration task reflects in part variations in phonological skills and letter-sound knowledge.

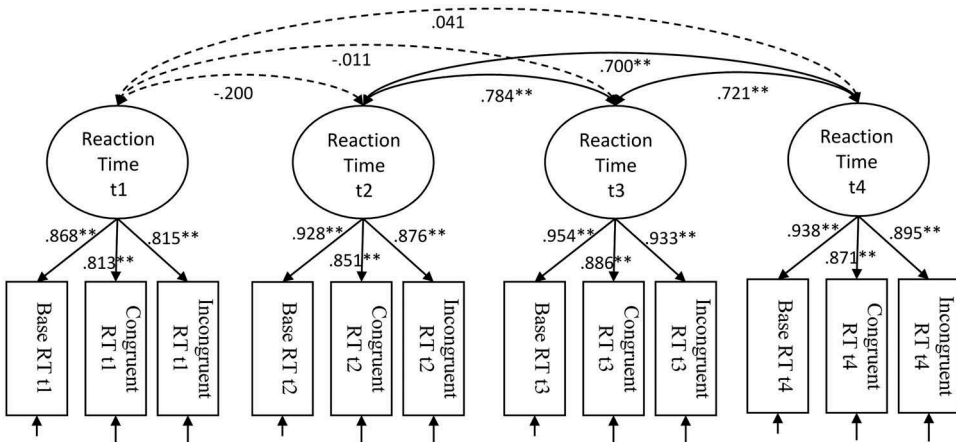


Figure 4. Confirmatory factor analysis showing longitudinal stability of a latent factor representing response speed on the letter-sound integration task. All coefficients are standardized.

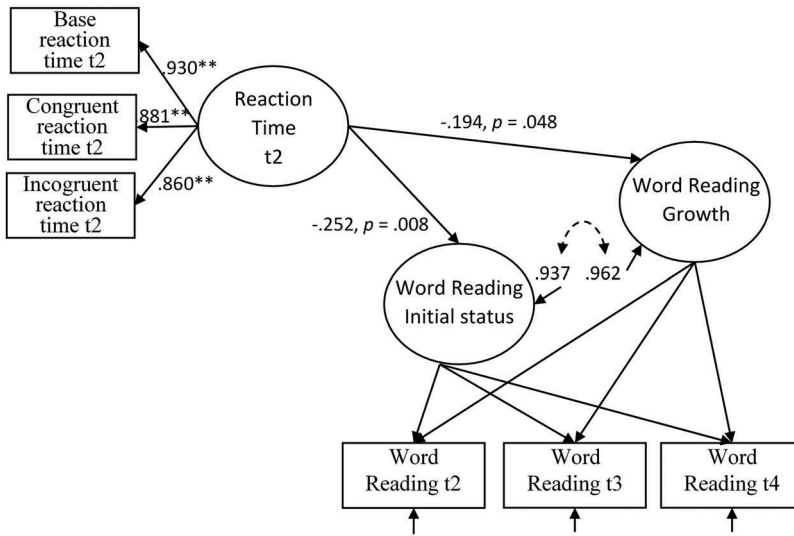


Figure 5. Growth model of relationship between overall response speed on the letter-sound integration task and early reading development. All coefficients are standardized.

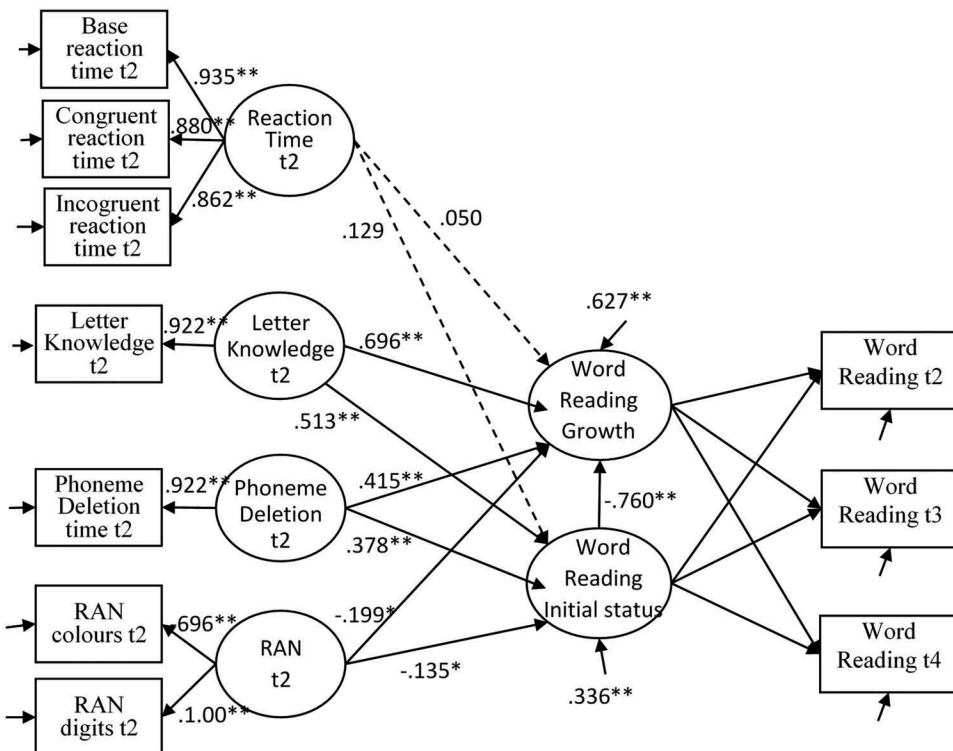


Figure 6. Growth model illustrating the relationship with early reading development of response speed on the letter-sound integration task, phoneme awareness, letter-sound knowledge and RAN. All coefficients are standardized.

Table 2. Correlations among the latent variables for the model shown in Figure 6.

	1.	2.	3.	4.	5.	6.
1. T2 Reaction Time	1					
2. T2 RAN	.33**	1				
3. T2 Letter Knowledge	-.39**	-.54**	1			
4. T2 Phoneme Deletion	-.34**	-.48**	.51**	1		
5. Intercept	-.24**	-.55**	.73**	.66**	1	
6. Slope	-.22*	-.31**	.39**	.31**	.08	1

Possible reciprocal relationships between RAN and reading development

Finally, we wanted to examine potential reciprocal relationships between reading development and the development of RAN, phoneme awareness and reaction time. We estimated four models where the growth of these three variables were estimated in parallel with the growth of reading. In particular, we were interested in whether the initial status of one process predicted the growth of the other process when the initial status of the other process was controlled. As growth was nonlinear for all of the measures we freely estimated the factor loading for the middle time point. There were negative residuals for the first time point for reading, RAN colours, phoneme awareness and reaction time, however, as they were all non-significant we fixed them to zero.

As the growth of reading had a different relationship with the growth of RAN colours compared to RAN digits we estimated the two growth processes in separate models. Simplified versions of these models are shown in Figure 7a and 7b for the colour and digit versions respectively. Initial status for both RAN digits and colours predicted the growth of reading after controlling for initial levels of reading; these coefficients are negative meaning shorter times on the RAN tasks were associated with faster growth in reading. In addition, there was a reciprocal relation between reading and the growth of RAN digits: higher levels of initial reading skill were associated with slower rates of growth in RAN digits. This pattern is consistent with the view that children with the weakest reading skills at the beginning of the study, may have had insecure knowledge of digit names, and that which allowed for growth in digit naming speed as reading development increased. Furthermore, there were

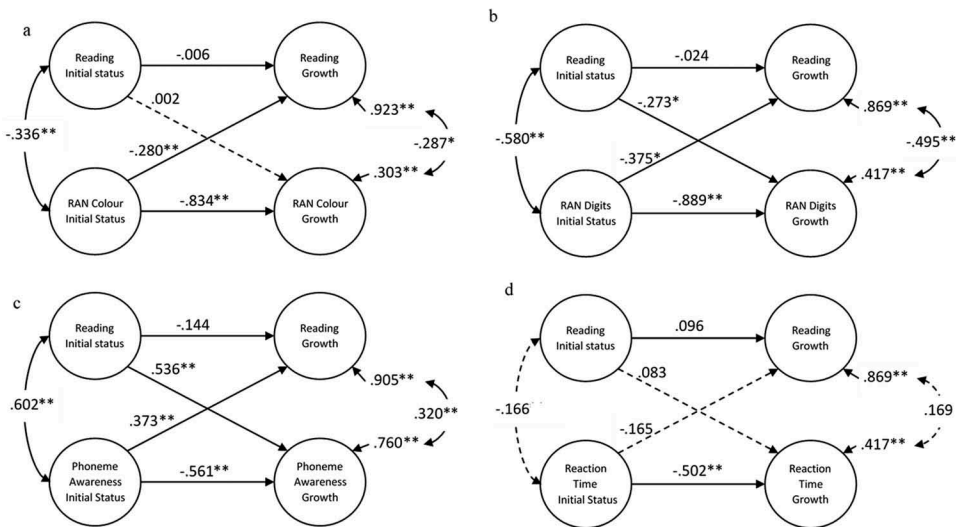


Figure 7. Growth models showing reciprocal relationships between RAN Digits and early reading development (b) and phoneme awareness and early reading development (c). All coefficients are standardized.

significant correlations between the growth of the two RAN constructs and the growth of reading. The model fit was good for both RAN colours, $\chi^2(6) = 9.003$, $p = .173$, RMSEA = .051 (10% CI = .000-.116), CFI = .996, TIL = .991, and RAN digits, $\chi^2(5) = 6.616$, $p = .251$, RMSEA = .041 (10% CI = .000-.115), CFI = .998, TIL = .994, respectively.

There were also reciprocal relationships between phoneme awareness and reading as the initial status of one process predicted the growth of the other process (see [Figure 7c](#); children with higher initial reading levels showed greater growth in phoneme awareness, and similarly children with higher initial levels of phoneme awareness showed a greater growth in reading. In addition, there were significant correlations between the growth of the processes after controlling for starting levels in the other processes. The model fit was good for this model, $\chi^2(7) = 7.773$, $p = .353$, RMSEA = .024 (10% CI = .000-.095), CFI = .999, TIL = .998.

No reciprocal relationships were found between the latent reaction-time construct and reading (see [Figure 7d](#)); the model fitted the data well, $\chi^2(56) = 65.836$, $p = .173$, RMSEA = .030 (10% CI = .000-.057), CFI = .995, TIL = .994.

Discussion

This longitudinal study examined the relationships between developing reading skills and a range of predictors of reading in a sample of 191 children assessed at four time points during their first year of formal reading instruction (mean ages: 4;6 years to 5;6 years). Measures included well established predictors of reading (phoneme awareness, letter-sound knowledge, RAN), as well as a novel measure of automatic letter-sound integration.

We used latent growth curve modelling to examine relationships between these measures and reading development. This statistical technique eliminates measurement error by constructing latent variables that take only the common variance of their indicators into account. It also allows potential reciprocal effects to be examined. Since measures of reading were at floor at the start of the study, growth models were estimated from T2 onwards.

The current longitudinal study used a measure of letter-sound integration that had been used previously in a concurrent study with older children (Clayton & Hulme, 2018). The results from the letter-sound integration task showed a robust priming effect, which was in evidence as soon as children had learned letter-sound correspondences (from T2 onwards after just 4 months in school). Thus, we have evidence of letter-sound integration emerging earlier than suggested by some previous research (Froyen et al., 2009). The priming effect reported from T2 onwards directly replicates the pattern observed in our previous study with the same task (Clayton & Hulme, 2018), but extends this finding to younger children in the earliest stages of learning to read. In line with our earlier findings from a concurrent study with older children (Clayton & Hulme, 2018) the extent of the priming effect on the letter-sound integration task was not a predictor of reading in this younger sample. The presence of robust priming effects on the letter-sound integration task at T2 demonstrates that the task is sensitive to children's knowledge of letter-sound relationships, but it is striking that the degree of facilitation on this task is not a reliable predictor of individual differences in reading development. It would be useful for future studies, however, to examine whether alternative measures of letter-sound integration can be developed that are related to individual differences in reading development.

Faster response speeds on the different conditions of the priming task were associated with better letter-sound knowledge, phoneme awareness and RAN performance. These findings are consistent with previous results showing overall slower responding on the task in children with dyslexia (Clayton & Hulme, 2018). In the current study, a latent variable representing the shared variance in speed of response across conditions of the letter-sound priming task was found to predict both reading status at T2 and growth of reading between T2 and T4. However, once letter-sound knowledge, phoneme awareness and RAN were added to this model, it did not predict any additional unique variance. This pattern suggests that overall reaction times on the letter-sound priming task

are related to reading ability, but not as well as better established measures (letter-sound knowledge, phoneme awareness and RAN).

Our growth models clearly showed that letter-sound knowledge, phoneme awareness and RAN were all strong, independent predictors of word reading, predicting both initial reading status of children after only a single term of formal reading instruction and growth in reading over the remainder of the year. These longitudinal results measured across a relatively narrow time window extend those from previous research examining predictors of early reading development (Allor, 2002; Lervåg, Bråten, & Hulme, 2009; Lervåg & Hulme, 2009; Muter et al., 2004), and highlight the important role phonological skills play in the earliest stages of learning to read.

An important finding in this study is that both phoneme awareness and alphanumeric RAN share a reciprocal relationship with reading. Learning to read appears to lead to improved performance on phoneme deletion and RAN digits at later time points. This finding is consistent with previous research reporting reciprocal relationships between phoneme awareness and early word reading development (Burgess & Lonigan, 1998; Hogan, Catts, & Little, 2005; Perfetti et al., 1987; Peterson et al., 2017). Some previous research has also reported that literacy development influences subsequent improvement in alphanumeric RAN (Compton, 2003; Wolff, 2014). Crucially, although a strong longitudinal relationship between alphanumeric and non-alphanumeric RAN suggests that both types of RAN rely on the same underlying cognitive mechanisms (Lervåg & Hulme, 2009), reciprocity between RAN and reading growth in the current study was only found for RAN digits and not RAN colours. This finding that initial reading skills predict growth in digit (alphanumeric) but not colour (non-alphanumeric) RAN is consistent with the view that familiarity with alphanumeric stimuli may be intimately related to increases in early reading skills. At T2 the children were roughly 4 years 9 months old and had been in school for a little over one term, hence we might expect knowledge of digit names to be less than fully automatized at this stage of development, whereas children of this age would be fully familiar with colour names. The current findings are, therefore, consistent with the unidirectional relationship between non-alphanumeric RAN and reading reported in Lervåg and Hulme (2009). The current results differ slightly from those in Peterson et al. (2017), who found that the reciprocal relationship between RAN and reading development extended to non-alphanumeric RAN. However, the reciprocal effect in Peterson and colleague's study was limited to the very youngest children in the sample (pre-k) and was absent in older children for whom RAN colours still predicted reading (1st grade). It is possible that by T2 the children in the current study were already too old to show reciprocity between non-alphanumeric RAN and early reading accuracy, whereas increasing facility in the retrieval of letter and digit knowledge fed in to a demonstrable bi-directional relationship with alphanumeric RAN.

The finding that both phoneme awareness and alphanumeric RAN share a reciprocal relationship with early reading development has important implications for both theory and practice. It suggests, not only that the development of phonemically structured phonological representations are critical for learning to read, but that reading experience, in turn, exerts a positive influence on the development of such representations. This pattern raises the possibility that the phonological deficit in dyslexia, especially in older children, may be partially a consequence of reading failure (Peterson et al., 2017). From a clinical perspective, tests of phoneme awareness and RAN have great benefits as assessment tools for children at risk of reading difficulties, not least because they are simple to administer. However, if the relationship between these predictive skills and reading is reciprocal then assessment using these skills potentially loses an element of predictive power in identifying children with reading disorders (Hogan et al., 2005; Peterson, 2017), at least later in development, once reading is established.

To conclude, this longitudinal study of children during the first year of reading instruction provides further support for a close relationship between phonological skills (phoneme awareness, letter-sound knowledge and RAN) and early reading development. In the case of phoneme awareness and alphanumeric RAN, this relationship appears to be a bi-directional one, with increasing reading accuracy leading to improvements in these core phonological skills. By contrast, the study

found that automatic integration of letter-sound correspondences could be measured early in development (after just 4 months of formal reading instruction) but did not predict variations in word reading skill. Furthermore, although overall response speed on the letter-sound integration task did predict growth in reading, it did not provide a unique contribution over and above letter-sound knowledge, phoneme awareness and RAN.

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