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Paired-associate learning, phoneme awareness, and learning to read

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Abstract

We report two studies examining the relations among three paired-associate learning (PAL) tasks (visual–visual, verbal–verbal, and visual–verbal), phoneme deletion, and single-word and nonword reading ability. Correlations between the PAL tasks and reading were strongest for the visual–verbal task. Path analyses showed that both phoneme deletion and visual–verbal PAL were unique predictors of a composite measure of single-word reading and of irregular word reading. However, for nonword reading, phoneme deletion was the only unique predictor (and visual–verbal PAL was not a significant predictor). These results are consistent with the view that learning visual (orthography) to phonological mappings is an important skill for developing word recognition skills in reading and that individual differences in this ability can be tapped experimentally by a PAL task.

Keywords: Learning to read; Phoneme awareness; Paired-associate learning

Introduction

Reading is a skill that is learned slowly and incrementally, and a degree of reading fluency is one of the key attainments of the first several years of formal education. Viewed in this way, it is clear that reading must depend critically on long-term memory

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mechanisms. In this article, we consider the possible role of paired-associate learning (PAL) mechanisms as a possible foundation for the acquisition of children's reading (visual word recognition) skills. In particular, we investigate whether visual–verbal PAL skill may be particularly important for learning to read.

Visual–verbal PAL might play a number of roles in learning to read. One critical foundational skill for learning to read is the acquisition of letter-sound knowledge (Byrne, 1998; Muter, Hulme, Snowling, & Stevenson, 2004). The learning of letter sounds is a clear example of visual–verbal PAL. The child must learn the visual representation for each letter (stimulus learning), the phonological representation for each letter sound (response learning), and the associations between letters and their sounds (stimulus–response association formation). These letter-sound associations are essentially arbitrary, and learning them takes a significant period of time during the preschool and early school years. Problems in learning letter sounds might reflect problems in stimulus learning (learning the letter shape), response learning (learning the letter sound), or stimulus–response association formation (associating the shape with the sound).

At a higher level, when developing an early sight vocabulary, the process of learning to associate printed words (orthography) and their pronunciations (phonology) can also be viewed as an example of PAL. Once again, this depends on forming visual (orthographic) and phonological representations and on creating associative links between these two classes of representation (e.g., Hulme, 1981). At least during the early stages of learning to read, such associative learning may well represent a form of PAL for the child.

Perhaps the first evidence for the importance of PAL as a critical process for learning to read came from studies of children with dyslexia. Several early studies showed that dyslexic children have difficulty in learning to associate nonsense syllables with abstract visual forms (Gascon & Goodglass, 1970; Vellutino, Steger, Harding, & Phillips, 1975), although they performed normally on nonverbal PAL tasks such as learning to associate one abstract shape with another (Goyen & Lyle, 1971; Vellutino et al., 1975). These studies were generally consistent with the view that children with dyslexia exhibit deficits on PAL tasks whenever such tasks involve a verbal component (for a review, see Hulme, 1981). Vellutino, Scanlon, and Spearing (1995) extended this work to show that poor readers were worse at learning to associate Chinese ideographs or strings of novel orthographic characters with spoken words than were control children of similar nonverbal ability, particularly when the words were abstract in meaning. They concluded that the poor readers' difficulty in reading and visual–verbal PAL probably reflected a common phonological coding deficit. This suggestion would lead us to expect that if measures of phonological skill and (verbal) PAL were examined in the same children, the variance in reading skill predicted by PAL would largely be shared with variance predicted by measures of phonological skill.

More recently, Messbauer and de Jong (2003) reported a study that compared a group of dyslexic Dutch readers with groups of chronological-age (CA) and reading-age (RA) controls on nonverbal and visual–verbal PAL tasks. No group differences were found on the nonverbal (visual–visual) PAL task. However, on the visual–verbal PAL tasks (involving both words and nonwords), the performance of the dyslexic readers was worse than that of the CA controls and was equivalent to that of the RA controls. Messbauer and de Jong argued that phoneme awareness and verbal learning might reflect the same underlying difficulty because the reader group difference in visual–verbal PAL diminished when variation in phoneme awareness was taken into account. However, because the dyslexic readers had difficulty with visual–verbal PAL tasks involving both words and nonwords, Messbauer and de Jong argued that this difficulty did not reflect problems in the acquisition of new phonological representations but was more likely to represent a general phonological learning difficulty.

A number of recent studies suggest that variations in the ability to learn visual–verbal associations may well make a contribution to children's reading acquisition that is separable from measures of phonological ability. Wimmer, Mayringer, and Landerl (1998) compared German dyslexic and normal readers on a range of tests, including a PAL task that involved learning the nonsense names of three different animal pictures. They found that although the reader groups did not differ on tests of phonological awareness, the children with dyslexia learned fewer of the nonsense names. Mayringer and Wimmer (2000) extended this study to show that this deficit in the children with dyslexia was restricted to the learning of nonsense names; when familiar short words were used, the dyslexic children performed normally. Although this finding leaves open the possibility that it is individual differences in new word (phonological) learning that accounts for variation in reading skills (e.g., Messbauer & de Jong, 2003), it is nonetheless consistent with the idea that visual–verbal PAL plays an important role.

Windfuhr and Snowling (2001) investigated the relative importance of phonological skills and PAL as predictors of variations in reading skill in a large sample of normally developing readers of English who differed widely in age. They found that a visual–verbal PAL task that involved learning to associate nonwords with abstract shapes made a unique contribution to predicting variations in reading ability even after controlling for the effects of age, IQ, phoneme deletion ability and rhyme oddity. The phonological awareness tasks (phoneme deletion and rhyme) also accounted for unique variance in reading skill after controlling for the effects of PAL and the other variables.

These previous studies suggest that visual–verbal learning may have a special status over other learning tasks in predicting reading performance. However, it is not clear whether the importance of PAL as a predictor of reading applies equally to within-mode learning tasks (i.e., visual–visual and verbal–verbal). Windfuhr and Snowling (2001) included only a single visual-to-verbal learning task in their study. As noted previously, the visual–verbal PAL task used by Windfuhr and Snowling involves at least three processes: learning the visual representations for each nonsense form (stimulus learning), learning the phonological representation for each of the nonwords (response learning), and learning the associations between the nonsense forms and their paired nonwords (stimulus–response association formation). Arguably, we might expect problems in learning new nonword forms to place heavy demands on phonological processing skills that, in turn, are known to be critical for learning to read. In this view, problems with visual–verbal PAL might simply reflect a phonological processing weakness that leads to difficulty in learning the phonological representations of the nonwords. If this were the case, verbal–verbal PAL should correlate at least as well with reading ability as does visual–verbal PAL. In the current study, therefore, we included two within-modality PAL tasks: a verbal–verbal PAL task and a visual–visual PAL task. If the visual–verbal PAL task is a stronger predictor of reading ability than either of the within-modality PAL tasks (visual–visual or verbal–verbal), this would suggest that the creation of visual–verbal associations plays a very specific role in learning to read that cannot simply be reduced to problems of association formation in general or to the process of learning either visual or phonological representations (which are tapped by the other two tasks).

A subsidiary question in the current study concerns whether, if paired-associate learning is a critical foundation skill for learning to read, it varies in importance for learning words of different types. Current models of reading and reading development suggest that different resources are used for reading different types of words (e.g., Harm & Seidenberg, 1999; Jackson & Coltheart, 2001; Plaut, McClelland, Seidenberg, & Patterson, 1996). Specifically, if reading nonwords depends on a process that allows generalization from mappings between orthography and phonology (as has been argued), reading these items will be critically dependent on the nature and quality of the phonological representations that allow such mappings to be learned (Harm & Seidenberg, 1999; Hulme, Quinlan, Bolt, & Snowling, 1995; Plaut et al., 1996). In contrast, the relations between orthography and phonology are less systematic for irregular or exception words and presumably depend on some degree of partly arbitrary associative learning between orthographic and phonological codes (Harm, McCandliss, & Seidenberg, 2003). It could be predicted, therefore, that visual–verbal PAL may be a particularly strong predictor of variations in exception word reading and a much weaker predictor of nonword reading. Conversely, phonological skill might be expected to be a strong predictor of variations in nonword reading skill and a weaker predictor of variations in exception word reading ability.

To assess these possibilities, reading was assessed by a number of measures in the current study. Lists of regular and irregular words and nonwords, in addition to a standardized measure of word recognition ability, were presented to children. Phonological skills were assessed by a phoneme deletion task given evidence that this task is the strongest known predictor of variations in reading skill in children of this age and younger (Hulme, 2002; McDougall, Hulme, Ellis, & Monk, 1994; Muter et al., 2004). A critical issue is whether any effects of PAL on reading can be explained in terms of an underlying deficit in phonological skills (Vellutino et al., 1995) or whether instead it needs to be accepted that phonological skills and PAL are separable sources of variation in children's reading development.

Experiment 1

Method

Participants

A total of 66 primary school children (36 girls and 30 boys), between 7 years 7 months and 11 years 10 months of age (average age = 9 years 10 months, $SD = 13.3$ months), participated in the experiment. They were recruited from two local-authority-controlled schools in the city of York in the United Kingdom. All children spoke English as their first language.

Design

All children were assessed on a range of reading tasks, together with measures of phoneme deletion ability and PAL. This testing was conducted over four 20- to 30-min sessions approximately 1 week apart. Assessments of reading and phonological awareness were carried out during the first session. Each of the remaining three sessions included one of the three PAL tasks, which were presented in a counterbalanced order.

Tests and materials

Paired-associate learning. Each child took part in three PAL tasks on separate days. In each of the tasks, the experimental materials (sets of nonwords and/or shapes) were counterbalanced across conditions so that each set of stimuli occurred equally often across the relevant conditions. The order of the stimuli within each of the six sets was fixed.

Nonwords. Three sets of five phonotactically legal one-syllable CVC (consonant–vowel–consonant) nonwords were used: Set 1 (huk, fot, jat, zog, raz). Set 2 (dof, teg, lum, mab, sep), and Set 3 (kel, gug, nid, bim, vob).

Shapes. Three sets of abstract shapes of low association value were used. These were six-sided shapes drawn from the Vanderplas and Garvin (1959) set (numbers 16–30 inclusive). These were then randomly assigned to three sets of five: Set 1 (numbers 28, 25, 17, 27, 26), Set 2 (numbers 20, 16, 22, 24, 19), and Set 3 (numbers 23, 30, 18, 29, 21). The black shapes (approximately 100 × 100 mm) were presented on cards (210 × 150 mm), with each set having a different background color.

Reading measures

WORD basic reading. A standardized untimed test of single word reading, Wechsler Objective Reading Dimensions (WORD), was used (Wechsler, 1993).

Regular, irregular, and nonword reading. Each child was asked to read aloud a list of 30 regular words (e.g., free, nerve, middle) and 30 irregular words, (e.g., lose, island, tomb) matched for frequency and imageability, grammatical class, and the number of letters (taken from Castles & Coltheart, 1993). In addition, 30 nonwords (also from Castles & Coltheart, 1993) represented different levels of orthographic complexity and included monosyllabic and disyllabic items.

Phoneme deletion. A phoneme deletion measure from McDougall et al. (1994) was used. In this task, the child hears a spoken monosyllabic nonword and is required to delete a specified phoneme. There were 24 items, and in all cases deletion of the specified phoneme resulted in a word. For example, deleting /b/ from the nonword /beis/ produces the word *ice*.

Procedure

Children were tested individually in a quiet part of the school. The instructions given by the experimenter were as follows: "In this game, you are going to learn which shape [word] goes with another shape [word]. Watch [Listen] carefully and try to remember which shape [word] goes with which shape [word]." Specific procedural details for each of the learning tasks are described in the following paragraphs.

Visual–visual PAL. One set of shapes was laid out in a row in front of the child. The experimenter held the second set. One at a time, the experimenter placed the shape from his set adjacent to the paired shape from the child's set, stating the association, "This shape goes with this shape." The two cards were presented together for 5 s, and then the experimenter removed the card. After all five associative pairings had been presented once, both sets of shapes were shuffled to prevent the use of positional cues to aid recall. The experimenter then presented each of the five cards, posing the question, "Which shape goes with this shape?" The child needed to point to the appropriate shape in his or her set. Feedback was given as to whether the child's selection was correct ("Yes, that's right") or incorrect ("No, the right answer is ___"). In total, five study/test trials (25 responses) were presented, with the order of recall being random for each trial. The number of correct matches made by the child was recorded.

Verbal–verbal PAL. Initially, the child was asked to repeat aloud each of the nonwords in turn. When the experimenter was satisfied that the child could clearly pronounce each nonword correctly, the learning procedure began. The experimenter presented each pair of words in turn twice, stating the association (e.g., "*Huk* goes with *dof* [2-s interval], *huk* goes with *dof*"). All stimulus nonwords were from one set, and all paired response nonwords were from another set. At the end of the learning phase, the experimenter said, in a pseudo-random order, each of the stimulus nonwords, posing the question (e.g., "What goes with *huk*?"). The child needed to respond with the appropriate response nonword (e.g., "*dof*"). Feedback was given for both correct and incorrect responses. In total, five study/test trials (25 responses) were presented, with the order of recall being different for each trial. The number of correct responses given by the child was recorded.

Visual–verbal PAL. Again, the child was asked to repeat aloud each of the nonwords in turn until the experimenter was satisfied that the child could clearly articulate each nonword. The experimenter then presented one shape at a time, stating the nonword with which it was associated twice (e.g., "This shape goes with *dof* [2-s interval], this shape goes with *dof*"). When all five shape–word pairs had been presented, the experimenter shuffled the cards. The experimenter then presented each card in turn, posing the question (e.g., "What word goes with this shape?"). Feedback was given as to whether the child's verbal response was correct or incorrect. In total, five study/test trials (25 responses) were presented, with the order of recall being random for each trial. The number of correct responses given by the child was recorded.

Results

Table 1 shows the mean scores for the measures of reading, phoneme deletion, and PAL. The children's scores on the WORD basic reading scale (Wechsler, 1993) show that they

Table 1
Means (and standard deviations) for the measures of reading, phoneme awareness, and PAL in Experiment 1 ($N = 66$)

	Mean	*SD*
Reading measures		
WORD reading (raw)	37.64	7.99
WORD reading (standardized)	100.03	13.28
Regular word (30)	26.48	4.65
Irregular word (30)	17.67	5.28
Nonword (30)	25.11	5.47
Phonological measure		
Phoneme deletion (24)	18.59	5.21
PAL tasks		
Visual–visual (25)	13.44	3.88
Verbal–verbal (25)	5.14	3.87
Visual–verbal (25)	8.85	4.36

Note. Maximum scores are in parentheses.

are reading at an average level for their age with a wide range of scores (standard score range = 74–129). Performance on the other three reading measures was in line with expectations in that the reading of phonetically regular words and nonwords was superior to that of irregular words.

Performance on the three PAL tasks showed a considerable variation in difficulty, with the visual–visual condition the easiest, the verbal–verbal condition the hardest, and the visual–verbal task at an intermediate level of performance. A repeated-measures analysis of variance (ANOVA) confirmed a significant difference among the three tasks, $F(2, 130) = 116.0$, $MSe = 9.84$, $p < .0001$, with pairwise comparisons (with Bonferroni adjustment) showing that all tasks differed significantly from each other.

Correlational analyses

We next examined the correlations between measures. Table 2 shows the correlations between raw scores on all tasks; simple correlations are shown above the diagonal, and partial correlations controlling for age are shown below the diagonal. The simple correlations show that all tasks are significantly and positively correlated with each other. The corresponding partial correlations, controlling for age, tend to be slightly weaker but show essentially the same pattern as the simple correlations. A number of patterns are evident in these correlations. All of the reading measures show strong correlations with each other and with phoneme deletion. The three measures of PAL show moderate correlations with each other, and there is a clear trend for the visual–verbal task to show the strongest correlations with reading ability and for the visual–visual task to show the weakest correlations with reading.

Modeling relations among measures of reading, phoneme deletion skill, and PAL

To assess the relative importance of the different tasks as predictors of individual differences in reading ability, we conducted a series of path analyses. Given the high correlations between our different measures of reading ability (WORD, regular word reading, irregular word reading, and nonword reading), we began by deriving a composite measure by summing the z scores for each of these measures. Before conducting these analyses, all of the relevant variables were residualized for age; thus, these models are examining age-indepen-

Table 2
Correlations among measures of reading, phoneme deletion, and PAL tasks in Experiment 1 (simple correlations above the diagonal, partial correlations controlling for age below the diagonal)

Measure	1	2	3	4	5	6	7	8
1. WORD (raw)		.83**	.92**	.76**	.69**	.35**	.37**	.56**
2. Regular words	.79**		.75**	.88**	.78**	.27*	.36**	.57**
3. Irregular words	.89**	.69**		.68**	.60**	.41**	.38**	.55**
4. Nonwords	.74**	.87**	.65**		.81**	.32**	.41**	.52**
5. Phoneme deletion	.67**	.76**	.56**	.80**		.37**	.40**	.49**
6. Visual–visual	.23	.16	.31*	.25*	.31*		.40**	.29*
7. Verbal–verbal	.38**	.36**	.41**	.41**	.40**	.39**		.52**
8. Visual–verbal	.49**	.51**	.48**	.47**	.45**	.21	.52**	

* $p < .05$.
** $p < .01$.

dent relations between variables. We used structural equation modeling, with maximum likelihood estimation procedures, to examine the relations between observed variables. The approach adopted was first to estimate a model with all possible correlations between the predictor variables (phoneme deletion, visual PAL, verbal PAL and visual–verbal PAL) and with all possible paths from the predictor variables to reading ability present. Nonsignificant correlations and paths were dropped iteratively to produce a simplified model in which all remaining relations are statistically significant.

The resulting simplified path model is shown in Fig. 1A and provides a remarkably good fit to the data. In this model, there are just two significant predictors of variations in

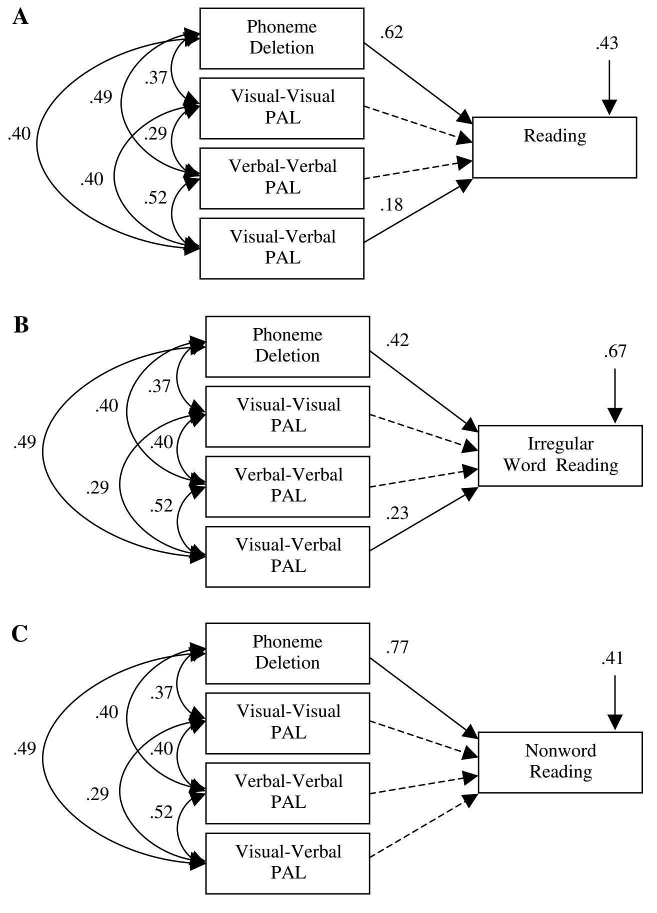

Fig. 1. Three path models showing the relations among word reading composite scores (A), irregular word reading scores (B), and nonword reading scores (C) and the phoneme deletion and PAL measures in Experiment 1. Fit indexes are as follows: (A) χ^2 (2, $N=66$) = 1.60, $p=.45$, $CFI=1.0$, $NFI=998$, $RMSEA=.000$ (90% $CI=.000$–.228); (B) χ^2 (2, $N=66$) = 2.30, $p=.32$, $CFI=1.0$, $NFI=.999$, $RMSEA=.050$ (90% $CI=.000$–257); (C) χ^2 (3, $N=66$) = 2.72, $p=.44$, $CFI=1.0$, $NFI=.996$, $RMSEA=.000$ (90% $CI=.000$–201). Solid paths represent statistically significant predictive relationships. Dashed paths represent nonsignificant predictive relationships that have been dropped from the simplified model. The arrow above the dependent variable in each model represents the error variance, that is, the proportion of variance not accounted for by the statistically significant predictors in the model.

reading skill: phoneme deletion and visual–verbal PAL ability. These two predictors account for an impressive 57% of the variance in reading ability.

Although the different measures of reading correlated highly with each other, it is notable that there are systematic and theoretically interesting variations in the size of correlations between the different reading measures. The highest raw correlation is between nonword reading and regular word reading ($r = .88$), and the lowest correlation is between nonword reading and irregular word reading ($r = .68$). As discussed in the Introduction, it could be argued that the cognitive processes responsible for learning to read irregular words will differ from those responsible for learning to read nonwords. More specifically, it might be argued that nonword reading will be heavily reliant on phonemic skills, whereas irregular word reading will be heavily reliant on visual–verbal PAL (because learning the pronunciation of an irregular word depends on making a partially arbitrary association between a string of letters and a pronunciation).

We decided to explore these theoretical possibilities in two more path analyses. Thus, we compared versions of the path model in Fig. 1A with two other versions in which the outcome variables were irregular word reading and nonword reading (once again, these measures were residualized for age). Our predictions were that the effect of phoneme deletion ability would be stronger in the model for nonword reading than in that for irregular word reading and, conversely, that the effect of visual–verbal PAL would be stronger in the model for irregular word reading than in that for nonword reading.

Fig. 1B shows the model for irregular word reading. In this case, the paths from both phoneme deletion and visual–verbal PAL are significant. This model gives a very good fit to the data and accounts for 33% of the variance in irregular word reading. Fig. 1C shows the model for nonword reading. This model again gives a remarkably good fit to the data. In this case, the path from phoneme deletion ability to nonword reading is strong (accounting for 59% of the variance in nonword reading ability), but the path from visual–verbal PAL is nonsignificant.

Discussion

This experiment has produced a very clear and theoretically interesting pattern of results. Variations in children's word recognition skills in reading are predicted independently by phoneme deletion ability and visual–verbal PAL. If we consider different aspects of word recognition, the reading of irregular words shows the same pattern as that for our composite measure, but for nonword reading visual–verbal PAL is of lesser importance and is not a significant predictor. This pattern of results is very much in line with the predictions outlined in the Introduction. We delay further consideration of the theoretical interpretation of these findings until after we present the results of Experiment 2.

Experiment 2

The pattern of predictive relations among reading, PAL, and phoneme awareness found in Experiment 1 was clear and in line with predictions from previous evidence and theory. However, it is notable that the PAL tasks were relatively difficult, with performance in the verbal–verbal condition being at a particularly low level. This raises the issue of whether the differences in predictive relations between verbal–verbal and visual–verbal PAL tasks might reflect differences in task difficulty. It seems at least possible that the weaker predictive relation between verbal–verbal PAL and reading, as compared with visual–verbal PAL and reading, might simply be a consequence of the lower levels of performance in the verbal–verbal condition.

To investigate this issue we changed the procedure in Experiment 2 to increase performance levels in the PAL conditions. To do this, we reduced the number of pairings to be learned in each condition from five to four and increased the number of learning trials given. We used six study-test trials in the visual–visual and visual–verbal conditions, and eight study-test trials in the verbal–verbal condition. We used a larger number of learning trials in the verbal–verbal condition in a deliberate attempt to produce equivalent levels of performance in the visual–verbal and verbal–verbal conditions. In this way, we hoped to eliminate differences in performance levels as a possible explanation for any differences in the strength of correlation between these two paired-associate learning tasks and reading. Finally, in this experiment, we recruited a larger sample of children with a narrower range of ages.

Method

The procedures used here were identical to those in Experiment 1 except for the differences noted in what follows.

Participants

A total of 127 primary school children (66 girls and 61 boys), between 7 years 11 months and 9 years 9 months of age (average age = 8 years 11 months, *SD* = 6.50 months), participated in the study. They were recruited from four local authority-controlled schools in the York and Durham areas. All of the children spoke English as their first language.

Procedure

The materials and procedure were identical to those in Experiment 1 except for using fewer stimuli and a larger number of learning trials in the PAL tasks. In this case, we used three sets of four nonwords—Set 1 (jat, sep, gim, dof), Set 2 (raz, kel, vib, fud), and Set 3 (mab, tef, zog, huk)—and three sets of four low-association value shapes from Vanderplas and Garvin (1959). There were six study/test trials in the visual–visual and visual–verbal conditions, and there were eight study/test trials in the verbal–verbal condition. The same measures of reading ability and phoneme awareness as in Experiment 1 were used.

Results

The means (and standard deviations) for all measures are shown in Table 3. The children's scores on the WORD basic reading test (Wechsler, 1993) show that they are reading at an average level for their age with a wide range of scores (standard scores of 69–128). It is apparent that although the children here are younger than those in Experiment 1, performance levels in the PAL tasks are higher with more or less identical numbers of correct responses in the visual–verbal and verbal–verbal tasks, $t < 1$. It appears, therefore, that using more learning trials in the verbal–verbal task has been successful in equating levels of

Table 3
Means (and standard deviations) for the measures of reading, phoneme awareness, and PAL in Experiment 2 ($N = 127$)

	Mean	*SD*	Range
WORD (raw)	34.96	8.99	8–50
WORD (standardized)	102.24	13.30	69–128
Regular words (30)	26.28	4.10	8–30
Irregular words (30)	16.05	4.45	0–27
Nonwords (30)	23.90	5.53	4–30
Phoneme deletion (24)	17.94	4.37	4–24
Visual–visual PAL (24)	17.91	3.89	9–24
Visual–verbal PAL (24)	14.65	5.67	0–24
Verbal–verbal PAL (32)	14.17	8.03	0–31

Note. Maximum scores are in parentheses.

performance. The visual–visual PAL task is easier than both the visual–verbal task, $t(126) = 6.19$, $p < .001$, and the verbal–verbal task, $t(126) = 5.28$, $p < .001$.

Correlations

To examine the interrelations among the measures of reading, phoneme deletion, and PAL, correlations were computed. Prior to this, the distributions of scores were examined to assess normality. Most measures showed no major deviations from normality with the exception of regular word reading, which showed negative skew.

The correlations between all measures are shown in Table 4, with simple correlations above the diagonal and partial correlations, controlling for age, below the diagonal. The pattern in the partial correlations is generally very similar to, but weaker than, the pattern in the simple correlations. A number of theoretically important patterns are evident in the partial correlations.

The reading measures correlate highly with each other (partial *r*s ranging from .63 to .81) and with phoneme deletion ability (partial *r*s ranging from .55 to .71), as expected. It can be seen that regular word reading and nonword reading are very highly correlated with

Table 4
Correlations among measures of reading, phoneme deletion and PAL tasks in Experiment 2 (simple correlations above the diagonal, partial correlations controlling for age below the diagonal)

	1	2	3	4	5	6	7	8	9
1. WORD (raw)		.94**	.77**	.77**	.66**	.56**	.19*	.26**	.04
2. WORD (std)	.99**		.76**	.61**	.71**	.61**	.17	.35**	.16
3. Regular words	.80**	.75**		.81**	.35**	.60**	.24**	.35**	.27**
4. Irregular words	.80**	.76**	.81**		.39**	.56**	.27**	.39**	.27**
5. Nonwords	.71**	.70**	.78**	.63**		.72**	.24**	.36**	.28**
6. Phoneme deletion	.62**	.61**	.60**	.55**	.71**		.22*	.38**	.36**
7. Visual–visual PAL	.19*	.16	.23**	.26**	.23**	.27**		.28**	.27**
8. Visual–verbal PAL	.41**	.40**	.39**	.42**	.52**	.39**	.52**		.52**
9. Verbal-verbal PAL	.28**	.26**	.36**	.36**	.50**	.40**	.50**	.50**	

* $p < .05$.
** $p < .01$.

each other and that, as expected, there is a lower correlation between irregular word reading and nonword reading. Also as expected, among the reading measures, irregular word reading shows the lowest correlation with phoneme deletion ($r = .56$) and nonword reading shows the highest correlation ($r = .72$).

The PAL measures show moderate correlations with each other (partial *r*s ranging from .28 to .50), and it is clear that the visual–verbal task tends to show the highest correlations with measures of reading ability.

Modeling the relations among reading, phoneme deletion, and PAL

As in Experiment 1, path analyses were used to assess the relative importance of phoneme deletion and PAL as predictors of individual differences in reading skill. In the initial analysis, a composite measure of reading ability, created by summing *z* scores for each of the reading measures (WORD single word reading, regular word reading, irregular word reading, and nonword reading), was used. Once again, in all of these analyses, all variables were first residualized for age so that the models presented are modeling the covariances between variables after the effects of age have been controlled.

The first model, using a composite measure of reading ability, is shown in Fig. 2A. There are two significant paths to the composite measure of reading: phoneme deletion and visual–verbal PAL. Together, these variables account for 48% of the variance in reading ability, and the model provides a remarkably good fit to the data.

As in Experiment 1, to assess possible differences in the role of PAL and phoneme awareness as predictors of irregular word reading and nonword reading, two more path models were created: one with irregular word reading and the other with nonword reading as the outcome variables. Fig. 2B shows the simplified path model for irregular word reading. Here, as in Experiment 1, both of the paths from phoneme deletion and visual–verbal PAL to irregular word reading are significant. Together, these variables account for 64% of the variance in irregular word reading ability, and the model provides a good fit to the data.

Fig. 2C shows the resulting simplified path model for nonword reading. In this case, the path from phoneme deletion to nonword reading is again significant, but the path between visual–verbal PAL and nonword reading was not quite significant ($p = .056$). Dropping this nonsignificant path resulted in a nonsignificant change in the fit of the model (difference in $\chi^2(1) = 3.611$, $p > .05$), and therefore the simplified model is to be preferred. In this model, phoneme deletion alone accounts for 49% of the variance in nonword reading ability, and the model provides a very good fit to the data.

General discussion

These two experiments have revealed a clear pattern of findings concerning the role of PAL mechanisms and phonological skills as predictors of variations in reading skill in normally developing children. First, we showed that visual–verbal PAL is a strong correlate of reading ability, in line with the findings of Vellutino et al. (1995), Wimmer et al. (1998), and Messbauer and de Jong (2003). This was true even after the very powerful effects of phoneme deletion ability were controlled, as was also found by Windfuhr and Snowling (2001). Second, we showed that the relation between visual–verbal PAL and reading does not simply reflect a general associative learning process given that verbal–

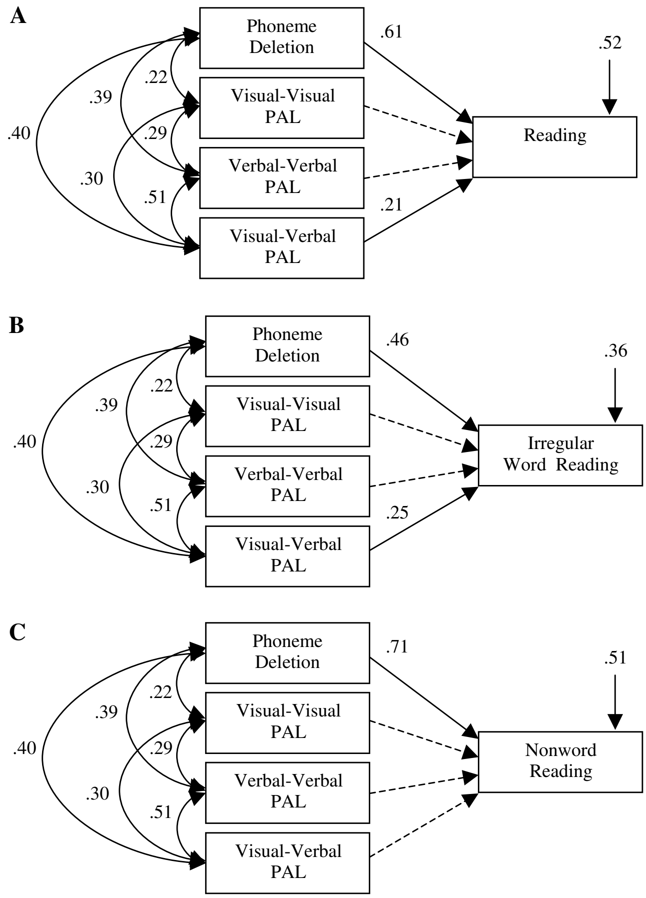

Fig. 2. Three path models showing the relations among word reading composite scores (A), irregular word reading scores (B), and nonword reading scores (C) and the phoneme deletion and PAL measures in Experiment 2. Fit indexes are as follows: (A) χ^2 (2, $N = 127$) = 1.208, $p = .55$, $CFI = 1.0$, $NFI = 993$, $RMSEA = .000$ (90% $CI = .000$–.152); (B) χ^2 (2, $N = 127$) = 2.406, $p = .30$, $CFI = .997$, $NFI = .983$, $RMSEA = .040$ (90% CI = .000–.257); (C) χ^2(3, $N = 127$) = 4.250, $p = .24$, $CFI = .992$, $NFI = .976$, $RMSEA = .058$ (90% $CI = 000$–.201). Solid paths represent statistically significant predictive relationships. Dashed paths represent nonsignificant predictive relationships that have been dropped from the simplified model. The arrow above the dependent variable in each model represents the error variance, that is, the proportion of variance not accounted for by the statistically significant predictors in the model.

verbal and visual–visual PAL are much weaker correlates of reading ability. Thus, an associative learning process that is specific to creating links between visual (orthographic) and phonological representations appears to play a key role in learning to read. At a more refined level, the role of visual–verbal PAL and phoneme deletion ability varies for learning to read different types of items; for reading English exception words, both visual–verbal PAL and phoneme deletion ability are important, whereas nonword reading appears to be critically dependent on variations in phonological skill but not on variations in visual–verbal PAL ability. We consider the implications of these findings for models of reading and reading development.

The findings of this study suggest that visual–verbal PAL is one of the critical foundations for learning to read. There are two distinct theoretical positions about how this relation might operate, and we argue that the current results cause some problems for each of these views. The first view is that the relation between visual–verbal PAL and reading is an example of the role of phonological skills in learning to read (Messbauer & de Jong, in press; Vellutino et al., 1995). According to this proposal, the effects of visual–verbal PAL on reading reflect the adequacy of underlying phonological representations that underpin the reading process (Harm & Seidenberg, 1999), a view for which we have much sympathy (Hulme et al., 1995; Hulme & Snowling, 1992). However, if this were the case, one might not expect it to account for unique variance in the prediction of reading ability once phoneme deletion ability is controlled. The current findings make clear that visual–verbal PAL draws on partially separate cognitive abilities from phoneme deletion. Although each task requires the child to establish a temporary phonological memory representation of a nonword, in the case of PAL this needs to be encoded into a durable memory representation and linked with a visual memory representation of a shape, whereas in the deletion task the temporary memory representation of a nonword needs to be segmented to produce a word. Further confirmation of basic differences between PAL and phoneme segmentation abilities comes from the findings of Wimmer et al. (1998), who reported that German dyslexic children showed PAL difficulty in the absence of deficits in phonological awareness.

Of course, it remains possible that both of the phonological tasks we investigated here (phoneme deletion and visual–verbal PAL) relate to reading because they each tap a different aspect of phonological processing. Our results establish that these two tasks at least tap into different aspects of phonological skill. Furthermore, the fact that the visual–verbal PAL task predicts reading skills independently of our verbal–verbal PAL task suggests strongly that the relation between reading and visual–verbal PAL cannot simply reflect the verbal (phonological) learning component of this task (because in that case verbal–verbal learning should relate as least as strongly to reading). Overall, we believe that this pattern of results suggests that a specifically cross-modal (visual–verbal) PAL mechanism plays a critical role in learning to read.

A second possible account of the role of PAL in learning to read is that it reflects the operation of some kind of general learning parameter (Byrne, 2005). Arguably, if this were the case, we would not expect variations in the prediction of reading from different PAL tasks. The fact that we found visual–verbal PAL to be a particularly strong predictor of individual differences in reading goes against this view. It appears, therefore, that visual–verbal PAL taps a mechanism that is more specific than a general-purpose associative learning process.

How is such a specific role for visual–verbal PAL best conceptualized in terms of the processes operating during reading development? As noted in the Introduction, it could be argued that visual–verbal PAL is directly involved in learning to read. The learning of letter names and sounds is a critical foundation for learning to read (Byrne, 1998), and individual differences in letter knowledge at school entry are one of the best predictors of early progress in learning to read (Adams, 1990; Bond & Dykstra, 1967; Chall, 1967; Muter et al., 2004). Moreover, and consistent with the current findings of separable sources of variance due to visual–verbal PAL and phoneme awareness, recent behavior-genetic analyses show independent genetic effects on phonological awareness and on print knowledge (including knowledge of letters) during preschool and first grade (Byrne, Wadsworth, Corley, Samuelsson, & Quain, 2005). Learning letter names and sounds is a very clear example of PAL, and delays in the acquisition of this knowledge present an obstacle for children learning to read, particularly if they also have poor phonological awareness (Snowling, Gallagher, & Frith, 2003). However, in the current studies of 7- to 11-year-old typical readers, the effects of visual–verbal PAL were not significant when nonword reading was considered alone (Figs. 1C and 2C). Because letter-sound knowledge obviously is necessary for reading nonwords, this suggests that the influence of PAL on reading skills is only partially mediated by letter knowledge.

Another possible role for visual–verbal PAL is in acquiring a sight vocabulary. Learning to pronounce written words clearly involves learning associations between orthographic (visual) and phonological representations (Jackson & Coltheart, 2001). According to Ehri's (1995, 1999) phase theory of learning to read, children learn sight words by forming connections between graphemes in the spellings and phonemes in the pronunciations of individual words. These connections secure the sight word in memory with its spelling, pronunciation, and meaning bonded together as a unit. Importantly, the process of forming connections allows readers to remember how to read not only regular words but also words with irregular spellings. As readers accumulate words in memory that share spelling patterns (e.g., -igh, -eak, -ing) with other words, these spelling patterns become functional units that can be used to form further connections and facilitate the task of retaining multisyllabic words in memory as sight words. Thus, within Ehri's model, the ability to consolidate connections between visual information at the letter and multiletter levels and phonemic and morphemic units of words is fundamental, and visual–verbal PAL can be considered to be a predictor of individual differences in the ability to consolidate these connections.

A different conceptualization of the "connection forming" or mapping process is embodied in connectionist models of reading and its development (Harm & Seidenberg, 1999; Plaut et al., 1996; Seidenberg & McClelland, 1989). According to such models, learning to pronounce printed words depends on creating associative links between sets of orthographic input representations and phonological output representations. In these models, repeated presentations of inputs (orthographic forms) give rise to (phonological) responses, and feedback is used to make those responses approximate more closely the desired response by modifying the associative links between input and output representations. Such supervised learning procedures could be thought of as computationally explicit visual–verbal PAL mechanisms. In such models, learning resources are often manipulated by varying the number of hidden units available for encoding mappings between orthography and phonology or by varying the rate of adjusting connection weights operating via hidden units. It is clear, therefore, that in models of this sort there is an explicit associative learning mechanism that operates across what are essentially arbitrary connections at least during the early stages of learning to read (Manis, Seidenberg, & Doi, 1999). The current findings are consistent with the view that variations in the efficiency of this mechanism will affect the speed of learning (and possibly also the adequacy of performance in the fully trained model).

A limitation of this study is that it involves only concurrent, rather than longitudinal, measurement. We argued that visual–verbal PAL may play a causal role in learning to read and that a deficit in such a learning process may be a cause of reading difficulty. In line with this view, longitudinal prospective studies of children at family risk for dyslexia show that one of the first manifestations of a literacy problem is slow acquisition of letter knowledge, a problem that predates deficits in phoneme awareness (Hindson et al., in press; Scarborough, 1990; Snowling et al., 2003). We argued that letter learning is a cardinal example of PAL. Further evidence that PAL may play a causal role in learning to read comes from the longitudinal data reported by Vellutino et al. (1996), who showed that early variations in PAL ability during kindergarten were predictive of later variations in reading skill and also of responsiveness to intervention. However, Vellutino and colleagues did not control for phoneme awareness when conducting their analyses. It is clearly possible that the correlations between PAL and reading ability observed in the current study and many others reflect a consequence, rather than a cause, of differences in reading skill. Further longitudinal studies are needed to help clarify the putative causal role of PAL as a critical determinant of reading development.

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