

**On the Role of Paired Associate Learning in  
Reading Development**



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## **Publications arising from this thesis**

### **Portions of this thesis appear in the following publications:**

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Litt, R. A., & Nation, K. (2014). The nature and specificity of paired associate learning deficits in children with dyslexia. *Journal of Memory and Language*, *71*(1), 71-88.

\*Note. Throughout this thesis, the term “we” is used to maintain consistency with the portions of this thesis appearing in academic papers. Despite this terminology, I certify that the work presented in this thesis is my own.

## **Short Abstract**

### **On the Role of Paired Associate Learning in Reading Development**

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Recent research suggests that visual-verbal paired associate learning (PAL) taps a crossmodal associative learning mechanism involved in reading acquisition. However, evidence from children with dyslexia indicates that deficits in visual-verbal PAL are strongly linked to the verbal demands of the task. The research presented in this thesis had two overarching aims: first, to dissociate crossmodal and verbal demands in driving the PAL-reading relationship, and second, to assess the hypothesis that visual-verbal PAL plays a causal role in reading development. To address the first aim, a series of experiments examined the relationship between reading ability and PAL tasks differing in modality (crossmodal, unimodal) and output demand (visual, verbal). The results supported a verbal account of the PAL-reading relationship. In typically developing children and children with dyslexia, only tasks with a verbal output demand (i.e., visual-verbal PAL, verbal-verbal PAL) demonstrated a relationship with reading ability. In children with dyslexia, poor performance was isolated to difficulties learning novel phonological forms, rather than difficulties specific to crossmodal associative learning. Furthermore, the ability to learn novel phonological forms was found to fully explain visual-verbal PAL performance across reading abilities. In a final experiment, the causal role of visual-verbal PAL in reading development was assessed. The results of a longitudinal study from the start to the end of kindergarten showed that visual-verbal PAL measured in pre-readers did not predict reading ability at the end of kindergarten. Instead, PAL performance was influenced by learning to read.

## **Long Abstract**

### **On the Role of Paired Associate Learning in Reading Development**

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Previous research in typically developing children has shown that visual-verbal paired associate learning (PAL) is an independent predictor of reading ability even after controlling for the contribution of phonological awareness (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2000) and RAN (Warmington & Hulme, 2012). These findings led to the hypothesis that visual-verbal PAL taps a crossmodal associative learning mechanism causally implicated in reading acquisition. In contrast, decades of research examining PAL deficits in children with dyslexia led to a far different conclusion with two lines of evidence suggesting that visual-verbal PAL deficits reflect difficulties with verbal, rather than crossmodal task demands. First, PAL deficits are specific to visual-verbal PAL; performance is unimpaired in non-linguistic PAL tasks, both within-modality (i.e., visual-visual) and between-modality (i.e., visual-auditory) (Messbauer & de Jong, 2003; Torgesen & Murphey, 1979; Vellutino et al., 1973; Vellutino et al., 1975). Second, the degree of impairment in visual-verbal PAL appears to be moderated by the phonological demands inherent in the verbal stimuli selected for the task (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003, 2006; Vellutino et al., 1995). This conclusion sits nicely within the phonological deficit hypothesis of dyslexia (Fowler, 1991; Snowling, 2001; Snowling, 1995; Snowling & Hulme, 1994). However, the interpretation of these findings is compromised by the fact that visual-verbal PAL has only been contrasted with nonverbal PAL tasks. Thus, it

remains possible that children with dyslexia experience difficulty specific to visual-verbal associative learning beyond that expected from their phonological deficits alone.

Chapters 2 and 3 of this thesis addressed the conflicting accounts of the PAL-reading relationship by dissociating crossmodal and verbal task demands. To do so, PAL performance was compared across four mapping conditions: visual-verbal, verbal-verbal, visual-visual, and verbal-visual. It was hypothesized that if crossmodal mapping demand accounts for the PAL-reading relationship, both visual-verbal and verbal-visual PAL should exhibit significant relationships with reading ability. In contrast, if verbal mapping demand accounts for the PAL-reading relationship, both visual-verbal and verbal-verbal PAL should exhibit significant relationships with reading ability.

Chapter 2 tested these hypotheses in typically developing readers. The results supported the verbal hypothesis. Only tasks requiring verbal output (visual-verbal, verbal-verbal PAL) significantly correlated with reading ability. Additionally, visual-verbal and verbal-verbal PAL were well represented by a latent “verbal-output PAL” factor. Structural equation modeling showed that this factor fully accounted for the PAL-reading relationship; visual-verbal PAL did not add anything to the prediction of reading above and beyond this latent factor. The results are incompatible with the crossmodal hypothesis, and instead demonstrate that verbal output is a necessary component of the PAL-reading relationship.

Chapter 3 extended these findings by reporting three experiments examining the locus and specificity of PAL deficits in children with dyslexia. Experiment 3.1 investigated the specificity of PAL deficits by dissociating crossmodal and verbal demands using the factorial design introduced in Chapter 2. Children with dyslexia exhibited selective deficits in visual-verbal and verbal-verbal PAL, but performed as well as their peers in verbal-visual and visual-visual PAL. Experiment 3.2 replicated

and extended these findings in a different sample of children with dyslexia and controls. The results showed the PAL deficits are driven by verbal, rather than crossmodal demands. Analyses of errors further supported this conclusion. Children with dyslexia made a higher proportion of errors that were phonological in nature than controls. Additionally, these errors were further from the target word (i.e. differing in more phonemic features) than the phonological errors of controls. Children with dyslexia did not commit a higher proportion of associative errors, indicating that their difficulties are not associative in nature. It was argued that these findings reflect a deficit in phonological form learning.

Experiment 3.3 isolated the verbal learning and associative learning stage of a visual-verbal PAL task. Children with dyslexia and age-matched controls were tested across two days. On day one, children were pre-exposed to the phonological forms in a novel word learning task. On day two, children learned to pair the same novel words with visual forms in a visual-verbal PAL task. Results of a linear mixed effects model revealed an item-specific relationship between novel word learning and later associative learning success. Furthermore, associative learning deficits were fully accounted for by preceding verbal learning deficits. These findings indicate that PAL deficits in dyslexia are not a consequence of difficulties with associative learning; instead, they are best characterized as deficits in phonological form learning.

Together, Chapters 2 and 3 showed that in both typically developing readers and children with dyslexia, only verbal-output PAL tasks demonstrate a relationship with reading ability. In both populations, there was no evidence for a specific relationship between crossmodal PAL and reading ability. These results resolved the conflicting accounts in the literature by demonstrating that a core verbal-output task component is responsible for the PAL-reading relationship.

Whereas Chapter 2 and 3 concerned the task demands that give rise to the PAL-reading relationship, Chapter 4 addressed the causal nature of the PAL-reading relationship. A longitudinal study examined the contribution of visual-verbal PAL in pre-readers to the prediction of reading ability at the end of kindergarten. The primary goal of the experiment was to evaluate whether visual-verbal PAL might play a causal role in reading development. Children were first assessed across a range of cognitive measures at the start of kindergarten, before they were able to read. The crucial question was whether PAL measured at the start of kindergarten (Time 1) would predict reading ability at the end of kindergarten (Time 2). The results of a longitudinal model were inconsistent with the hypothesis that individual differences in PAL cause variations in reading development. PAL in pre-readers did not emerge as a predictor of reading at the end of kindergarten. In contrast, growth in PAL performance was predicted by phonological awareness in pre-readers. Interestingly, an examination of the concurrent correlations between PAL and other cognitive predictors at each time point showed that whereas phonological awareness predicted PAL longitudinally, it was not related concurrently at Time 1. A concurrent relationship between the two measures only emerged at Time 2, after the onset of literacy instruction. It was argued that learning to read might bring about an increase in phonological awareness, particularly at the phonemic level, which in turn may serve to support the learning of novel words in PAL tasks. In sum, Chapter 4 showed that PAL is not causally implicated in reading development. Moreover, the observation that phonological awareness influences growth in PAL extended the findings of Chapters 2 and 3 by indicating that phonological skills are crucial in explaining PAL performance.

The experiments presented in this thesis demonstrated that despite the longstanding interest in the role of crossmodal mechanisms in learning to read,

variations in the ability to form crossmodal associations are largely unrelated to typical and atypical reading development. In contrast, the findings provided overwhelming support for the importance of phonological form learning (in tasks requiring output) in explaining the PAL-reading relationship. These results have important implications for our understanding of reading development, particularly dyslexia. Although it is clear that reading depends on the formation of orthography-phonology mappings, the results presented in this thesis suggest that the ability to form these mappings may be much more dependent on the ability to learn and retrieve the phonological forms from memory than the ability to learn the association between the two. Given that children with dyslexia are known to have difficulties in the acquisition of letter-sound mappings and orthographic knowledge, these results caution against interpreting these deficits as crossmodal in nature. Across experiments, children with dyslexia performed as well as their peers in verbal-visual PAL, a crossmodal task with lesser demands on verbal learning and output than visual-verbal PAL. Close examination of the error profiles of children with dyslexia, and explicit isolation of the task demands involved in visual-verbal PAL also supported the conclusion that these deficits stem from difficulties specific to the phonological component of the task. Theories of how phonological form learning may influence the quality of long-term phonological representations and subsequent reading development are discussed in the General Discussion.

## **Chapter 1: General introduction and overview of thesis**

*This chapter provides a broad overview of the existing literature relating to research presented in this thesis. It begins by reviewing the cognitive precursors of reading development in typically developing readers and the corresponding cognitive deficits observed in dyslexia. The focus then moves to theories of crossmodal learning mechanisms in reading development. Evidence for the role of crossmodal paired associate learning (PAL) in reading development is discussed, along with contradictory evidence from the literature on PAL deficits in dyslexia. The chapter concludes by outlining the opposing accounts of the PAL-reading relationship emerging from the literature, which leads to the research questions addressed by this thesis.*

Learning to read is a significant achievement. For beginning readers, recognizing a single word involves a complex set of processes, from the recognition of a string of visual symbols, to the translation of these symbols into their sounds, and the retrieval of the corresponding spoken word form. The research presented in this thesis addresses the cognitive abilities necessary for the development of the reading<sup>1</sup> system, with a focus on how learning mechanisms may place an additional constraint on reading development. The following chapter provides a broad overview of literature concerning the research questions addressed by this thesis, with more detailed critique of the relevant literature to follow in the individual chapters.

### *Cognitive precursors of reading development*

Before children can systematically decode words, they must acquire the alphabetic principle: the understanding that written language represents spoken language, and more specifically, that graphemes (letters) represent phonemes (sounds) within words (Byrne, 1998; Byrne & Fielding-Barnsley, 1989). Mastery of the alphabetic principle is one of the first major obstacles faced by beginning readers. It requires both an awareness of the sound structure of language, particularly at the level of the phoneme, and knowledge of letter-sound mappings (Byrne, 1998). When measured before the onset of reading, phoneme awareness and letter knowledge are powerful longitudinal predictors of learning to read (de Jong & van der Leij, 1999; Lervåg, Bråten, & Hulme, 2009; Lonigan, Burgess & Anthony, 2000; Muter, Hulme, Snowling, & Stevenson, 2004; Muter, Hulme, Snowling, & Taylor, 1998). Although the relationship between phoneme awareness and letter knowledge is highly reciprocal (Burgess & Lonigan, 1998; Muter et al., 2004; Perfetti, Beck, Bell, &

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<sup>1</sup> Throughout the thesis, the term *reading* will be used to refer to word recognition and decoding abilities

Hughes, 1987; Wagner, Torgesen & Rashotte, 1994), evidence suggests that both skills exert a causal influence on reading development (Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012; Lervåg et al., 2009; Muter et al., 2004). The most direct evidence for the causal role of phoneme awareness and letter knowledge in learning to read comes from training studies demonstrating that explicit training in these skills leads to improvements in reading, both in comparison to untrained control groups (Lundberg, Frost, & Peterson, 1988; Schneider, Kuspert, Roth, Vise, & Marx, 1997), and control groups trained in non-phonological oral language skills (Bowyer-Crane et al., 2008; Hulme et al., 2012). Moreover, training phoneme awareness and letter knowledge in concert leads to stronger subsequent gains in literacy than training either skill alone (Ehri et al., 2001; Hatcher, Hulme, & Ellis, 1994; Schneider, Roth, & Ennemoser, 2000), a finding that reinforces the necessity of both skills to the acquisition of the alphabetic principle.

The alphabetic principle allows for the development of accurate decoding skills, but becoming a skilled reader also involves a transition from effortful decoding to fluent and automatic word recognition. One skill that seems particularly important for the development of reading fluency is rapid automatized naming (RAN) (e.g., Lervag & Hulme, 2009; Savage et al., 2005; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004). RAN is a measure of the speed with which a set of familiar items, either nonalphanumeric (e.g., objects, colors), or alphanumeric (e.g., letters, digits) can be named. Although the nature of the abilities tapped by RAN remains a subject of much debate (see Kirby, Georgio, Martinussen, & Parrila, 2003 for a review), there is no doubt that it shares a concurrent and longitudinal relationship with reading ability (Lervag & Hulme, 2009; Manis, Doi, & Bhadha, 2000; Manis, Seidenberg, & Doi, 1999; Savage et al., 2005; Schatschneider et al.,

2004). Some researchers have questioned the independence of RAN from reading-related skills such as phonological awareness and letter knowledge (Bowey, McGuigan, & Ruschena, 2005), with particular concern arising from the observation that alphanumeric RAN is more strongly correlated with reading than nonalphanumeric RAN (Compton, 2003; Savage et al., 2005; Schatschneider et al., 2004). Despite the stronger relationship with alphanumeric RAN, studies measuring nonalphanumeric RAN before the onset of reading have nevertheless found that it exerts an independent, longitudinal influence on reading development (Caravolas et al., 2012; Caravolas, Lervåg, Defior, Málková, & Hulme, 2013; de Jong & van der Leij, 1999; Kirby et al., 2003; Landerl & Wimmer, 2008; Lervåg et al., 2009). These findings provide evidence for a causal influence of RAN on reading development.

Together, phoneme awareness, letter knowledge, and RAN are three of the strongest identified precursors of learning to read in alphabetic orthographies (Caravolas et al., 2012; Caravolas et al., 2013; Lervåg et al., 2009). Importantly, although differences in orthographic transparency (the consistency of spelling-sound mappings) influence the rate with which children become skilled readers, the relative importance of each of these predictors appears to be consistent across orthographies (Caravolas et al., 2012; Caravolas et al., 2013). Thus, early reading development in alphabetic orthographies seems to be underpinned by a “triad” of cognitive predictors.

*Cognitive bases of dyslexia*

For a substantial proportion of children, learning to read poses a significant challenge. Developmental dyslexia is a term used to describe the estimated 10-15% of school-age children who experience substantial and persistent difficulty learning to decode, spell, and recognize words with accuracy and/or fluency (e.g., Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). This difficulty is often unexpected in relation to cognitive functioning in other domains, and is not the consequence of primary sensory deficits such as hearing or vision loss. Contrary to popular belief, dyslexia is not a discrete all-or-nothing disorder; instead, it occurs on a continuum, with the cut-offs for meeting diagnostic criteria varying across studies, countries, and clinical practice (Shaywitz, 2003; Snowling & Hulme, 2012). Indeed, rather than follow a bimodal distribution (i.e., dyslexia, typical reading), reading ability is best described by a normal distribution, with dyslexia characterizing the lower tail of the distribution (Kovas, Haworth, Dale, & Plomin, 2007; Shaywitz et al., 1992). This view is supported by behavioral genetics studies showing that the genetic influences on the lower end of the distribution are largely the same as the genetic influences on reading more generally (Kovas et al., 2007; Plomin & Kovas, 2005). Thus, when it comes to reading disability, “the abnormal is normal” (Kovas et al., 2007, p. 60).

If, rather than representing a discrete disorder, dyslexia occurs along the continuum of normal reading development, it follows that understanding dyslexia requires an understanding of the processes involved in reading more generally. On this view, deficits associated with dyslexia must be shown to have some bearing on typical reading development before they are considered candidates for causal theories of reading disability. Consistent with the results of the large-scale longitudinal studies indicating that phoneme awareness, letter knowledge, and RAN are three foundation

skills for learning to read, children with dyslexia exhibit impairments in each of these skills. Difficulty acquiring letter knowledge is considered a risk factor for dyslexia (Byrne, Fielding-Barnsley, Ashley, & Larsen, 1997; Gallagher, Frith, & Snowling, 2000; Lefly & Pennington, 1996; Snowling, Gallagher, & Frith, 2003). Additionally, children with dyslexia are commonly impaired in RAN, with performance distinguishing them from their typically developing peers (Ackerman and Dykman, 1993; Denckla and Rudel, 1976; McBride-Chang and Manis, 1996; Meyer, Wood, Hart, & Felton, 1998; Wolf & Bowers, 1999). By far the most well-documented and pervasive deficits associated with dyslexia are phonological deficits. These deficits manifest themselves across a range of phonological tasks, including phonological awareness, nonword repetition, expressive naming, verbal short-term memory, and phonological learning (see Snowling, 2000, for a review). These widespread difficulties with phonological processing led to the phonological deficit hypothesis of dyslexia (e.g., Fowler, 1991; Snowling, 2001; Snowling, 1995; Snowling & Hulme, 1994). This theory proposed that dyslexia stems from a “core deficit” in the phonological system. Though the importance of phonological skills for reading remains unquestioned, more contemporary theories of dyslexia view phonological deficits as one of several cognitive and genetic risk factors that interact to give rise to dyslexia (Pennington, 2006; Snowling, 2008). This multiple deficit approach provides a better account of high rates of co-morbidity between dyslexia and other developmental disorders (e.g., specific language impairment, speech sound disorder, attention deficit hyperactivity disorder); additionally, it can accommodate the observation that while phonological deficits are a contributing factor to dyslexia, not all children with dyslexia demonstrate phonological deficits, and not all children with phonological deficits experience significant reading difficulties (Snowling, 2008). Instead, the likelihood of developing dyslexia depends on

a complex interplay of risk factors (e.g., deficits in phonological deficits, speed of processing), and protective factors (e.g., oral language).

### Establishing links between orthography and phonology

Longitudinal and training studies provide strong evidence for the role of letter knowledge, phonological awareness, and RAN in determining reading outcome. Yet to some extent, these measurements are already an outcome; they tell us about the degree to which these skills have already developed, but not about *how* these skills develop. That is, learning to read entails just that: *learning*. The most obvious form of learning inherent in reading is crossmodal in nature: it involves the learning of mappings between visual inputs (i.e., orthography) and verbal outputs (i.e., phonology). For the novice reader, this learning involves connections between individual graphemes (i.e., letters) and phonemes. As reading development progresses, mappings involve larger-grain and whole word mappings from orthography to phonology. Given this, it is not surprising that research has explored the extent to which learning to read can be considered a skill with its bases in crossmodal learning.

### *Crossmodal theories of reading development*

One of the first crossmodal theories of reading development was Birch and Belmont's (1964) theory of *crossmodal transfer*. According to this theory, the ability to recognize equivalencies between auditory and visual representations of information is crucial to early reading development, and delayed in developmental dyslexia. This theory was initially supported by findings of impaired matching of equivalent auditory and visual patterns in children with dyslexia. However, subsequent research largely

discredited these findings by showing the performance depended heavily on intelligence, working memory, and rapid temporal processing, rather than processes specific to crossmodal integration (Cummings & Faw, 1976; Zurif & Carson, 1970). Additionally, impairments on matching tasks were also observed in unimodal tasks (e.g. visual-visual, auditory-auditory), and thus not specific to crossmodal matching (Vande Voort & Senf, 1973, Vande Voort, Senf, & Benton, 1972).

In recent years, a range of behavioral and neuropsychological findings have generated renewed interest in the role of crossmodal mechanisms in reading development. One theory bearing many similarities to the crossmodal transfer hypothesis is Blomert and colleagues' theory of crossmodal integration (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Blomert, 2011; Blomert & Willems, 2010; Froyen, Willems, & Blomert, 2011). In a series of neurophysiological studies, the authors showed that adults and children with dyslexia do not process letters and speech sounds as single, integrated "audiovisual objects", even though they may explicitly know the associations between these letters and speech sounds (Blau et al., 2009; Blomert, 2011; Froyen et al., 2011). Letter speech sound integration may be particularly important for the development of skilled reading. In fact, the development of letter speech sound integration appears to coincide with increasing reading proficiency; children only begin to exhibit integration following four years of formal literacy instruction, and even then it occurs on a slower time course than that observed in adults (Froyen, Van Atteveldt, Bonte, & Blomert, 2008). Failure to integrate orthographic and phonological units would certainly provide an explanation for why fluency deficits remain notoriously difficult to remediate, even following successful remediation of decoding difficulties (Fletcher, Lyon, Fuchs, & Barnes., 2006; Torgesen et al., 2001). Although crossmodal integration is implicated in the development of

reading, it is reasonable to question whether it reflects a basic skill in learning the associations between orthographic and phonological units. Deficits in crossmodal associative learning would certainly impede the development of basic decoding and reading.

One approach to investigating the role of crossmodal associative learning in reading development is to utilize a paired associate learning (PAL) paradigm. PAL tasks involve learning to pair a stimulus item and a response item in memory. Participants are presented with stimulus-response pairs and later tested on their knowledge of these pairings in a series of test trials in which they are presented with the stimulus items and asked to recall the corresponding response items. Thus PAL performance depends on three crucial task components: learning the stimulus item, learning the response item, and learning the association, or mapping, between the two. Individual differences may arise at any or all of these components. By contrasting PAL tasks that differ in these mapping demands, experiments can identify the components of learning that may be important for reading development. For example, PAL tasks can vary in modality (i.e., crossmodal, unimodal) as well as input and output demand (i.e., visual, verbal). Most experiments that have used PAL to investigate early reading development probe visual-verbal mappings, in which children learn to associate spoken nonwords with novel visual symbols. For the purposes of this thesis, this form of PAL should be assumed unless otherwise specified.

When viewed in the context of early reading development, visual-verbal PAL may be considered a laboratory analogue of the processes involved in learning orthography-phonology mappings. To the novice reader, letters are simply abstract visual forms, and letter names and sounds are essentially novel phonological forms. Learning to read requires the establishment of arbitrary mappings between these visual

forms and their associated sounds. The crossmodal associative learning thought to be tapped by visual-verbal PAL is inherent in computational models of reading. In connectionist models, a learning algorithm acquires orthography-phonology mappings by strengthening the connection weights between orthographic inputs and phonological outputs according to the frequency of their co-occurrence (Seidenberg & McClelland, 1989). The integrity of this mechanism affects both the rate and accuracy of learning, and may be particularly important for the development of irregular word reading, in which the mappings from orthography to phonology are less consistent (Harm & Seidenberg, 1999). Though a crossmodal learning mechanism is computationally explicit in connectionist models, it is also implicit in dual-route models of reading (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). In dual-route models, accurate reading relies on previously acquired knowledge of both sublexical and lexical orthography-phonology mappings. Potentially, PAL represents the underlying learning mechanism responsible for the acquisition of these mappings.

Decades of research have demonstrated that children with dyslexia are impaired in visual-verbal PAL (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003, 2006; Vellutino, Scanlon, & Spearing, 1995; Vellutino, Steger, Harding, & Phillips, 1975). Moreover, the absence of deficits in visual-visual PAL demonstrates that these deficits cannot be explained by more general deficits in associative learning (Li, Shu, McBride-Chang, Liu, & Xue, 2009; Messbauer & de Jong, 2003; Vellutino et al., 1975). This robust pattern of findings is certainly consistent with the hypothesis that poor crossmodal associative learning may hinder the acquisition of orthography-phonology mappings; in addition to visual-verbal PAL deficits, children with dyslexia are slower to acquire letter knowledge (Carroll & Snowling, 2004; Pennington & Lefly, 2001; Scarborough, 1990), and require more exposure to written words before the

orthographic patterns become stored in memory (Ehri & Saltmarsh, 1995; Reitsma, 1983).

More general support for the role of crossmodal associative learning in reading development comes from studies demonstrating that visual-verbal PAL is an independent concurrent predictor of reading ability (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Windfuhr and Snowling (2001) showed that in primary school children (ranging in age from 6-11 years), visual-verbal PAL explained unique variance in reading ability after controlling for age, nonverbal intelligence, vocabulary, and phonological awareness. Both visual-verbal PAL and phonological awareness were unique predictors of word and nonword reading, suggesting that they tap separate mechanisms involved in reading. Additionally, visual-verbal PAL accounted for unique variance in word reading even after controlling for decoding ability (by entering nonword reading in the regression first), providing support for the theory that crossmodal associative learning plays a role in forming word-specific orthographic representations (Ehri, 1992; Ehri, 2005; Windfuhr & Snowling, 2001).

Not only is visual-verbal PAL distinct from phonological awareness, but it also seems to be distinct from RAN. Warmington and Hulme (2012) found that visual-verbal PAL predicted concurrent reading speed and accuracy (for words and nonwords) independent from the contribution of both phonological awareness and RAN. This finding is surprising given that both visual-verbal PAL and RAN involve crossmodal associations; whereas PAL requires the learning of these associations, RAN requires rapid access and output of these associations. Many researchers have posited that deficient RAN may in effect be the outcome of poor (or unstable) associative learning (Lervåg et al., 2009; Manis et al., 1999). Yet, consistent with the findings of Warmington and Hulme (2007), other studies have reported only modest correlations

between visual-verbal PAL and RAN (Lervåg et al., 2009; Poulsen et al., 2012).

Additionally, Poulsen et al. (2012) directly tested the hypothesis that PAL mediates the relationship between RAN and reading, and found no evidence to support this view.

Thus, despite the obvious similarities between PAL and RAN, it seems that the underlying mechanisms responsible for their relationship with reading cannot be reduced to a common crossmodal component.

The independence of visual-verbal PAL from phonological awareness and RAN certainly supports the view that associative learning ability may place a constraint on learning to read, but is this effect specific to crossmodal associative learning? Hulme and colleagues (2007) set out to answer this question. The authors examined the relationship between three PAL mapping conditions (visual-verbal, visual-visual, and verbal-verbal) and reading ability in typically developing children in primary school. The design allowed for a test of the crossmodal hypothesis by examining whether visual-verbal PAL predicts reading ability after accounting for nonverbal associative learning (visual-visual PAL) and verbal learning (verbal-verbal PAL), both of which also differ from visual-verbal PAL in that they require unimodal rather than crossmodal associations. Consistent with previous research, visual-visual PAL was unrelated to reading ability. In contrast, both visual-verbal and verbal-verbal PAL correlated with reading ability, indicating that verbal task demands are at least partly responsible for the PAL-reading relationship. However, in a path model with all three mapping conditions and phonological awareness as predictors of reading ability, visual-verbal PAL was the only PAL task to predict unique variance in reading ability. This provides the best evidence to date for the specificity of the PAL-reading relationship to crossmodal associative learning.

One limitation with the experiments reviewed above is that they only assessed the PAL-reading relationship concurrently. In a latent variable longitudinal study, Lervåg and colleagues (2009) found that visual-verbal PAL assessed in pre-readers did not predict reading achievement approximately one year later (following three months of formal literacy instruction). This finding raises questions regarding the causal role of PAL in reading development. However, as the study was conducted in Norwegian, an orthography with transparent (i.e., consistent) spelling-sound mappings, the extent to which these results can generalize to opaque orthographies such as English remains an open question. Potentially, the importance of PAL in learning to read may increase as a function of the extent to which spelling-sound mappings are arbitrary.

Although this thesis focuses on the role of PAL in learning to read English, an alphabetic orthography, a growing body of evidence suggests that visual-verbal PAL is also important for learning to read in a non-alphabetic language, such as Chinese (Ho, Chan, Tsang, Lee, & Chung, 2006; Li et al., 2009; Yang et al., 2013). In fact, it has been argued that visual-verbal PAL may be more important for reading in non-alphabetic orthographies because the associations between print and sound are far more arbitrary than in alphabetic orthographies (Ho et al., 2006; Yang et al., 2013).

#### *An alternative interpretation of visual-verbal PAL deficits*

Despite the robust findings of visual-verbal PAL deficits in dyslexia, a range of findings question the extent to which visual-verbal PAL deficits are crossmodal in nature. For example, Vellutino and colleagues conducted a series of studies in which they compared children with dyslexia and controls on two crossmodal tasks: visual-verbal PAL, and visual-auditory PAL, a nonverbal, crossmodal task in which visual symbols were paired with oral sounds (e.g., humming). Children with dyslexia were

only impaired in visual-verbal PAL, indicating that their difficulties stemmed from the verbal response demands, rather than difficulties with learning crossmodal associations (Vellutino et al., 1975; Vellutino, Steger, & Pruzek, 1973). Moreover, subsequent research by Torgesen and Murphey (1979) showed that this finding held even when the output demands of the visual-auditory task (e.g., a sequence of three non-verbal oral sounds) were more closely matched to the visual-verbal demands (e.g., a nonword comprised of three phonemes).

Although these findings speak against global crossmodal deficits in dyslexia, this is not necessarily inconsistent with deficits specific to visual-verbal PAL. That is, a more limited definition of the term *crossmodal* may be warranted in respect to the abilities necessary for learning to read. The mappings acquired for reading are necessarily mappings between orthography and phonology, thus crossmodal mappings outside this domain are not necessarily expected to relate to reading ability. Indeed, contemporary crossmodal accounts of reading development confine their theories to mappings involving speech sounds (e.g., Blomert, 2011; Hulme et al., 2007).

However, the findings in regard to dyslexia remain difficult to interpret because children with dyslexia generally exhibit deficits in phonological processing (e.g., Fowler, 1991; Snowling, 1995; Snowling & Hulme, 1994; Vellutino, Fletcher, Snowling, & Scanlon, 2004), which could clearly account for poor performance specific to visual-verbal PAL, a task with verbal learning and output demands. Additionally, as studies contrasting visual-verbal PAL with visual-visual PAL have not included a unimodal verbal PAL task (i.e., verbal-verbal) it is unclear whether visual-verbal PAL deficits should be ascribed to crossmodal or verbal (i.e., phonological) demands (Mayringer & Wimmer, 2000; Li et al., 2009; Messbauer & de Jong, 2003, Vellutino et al., 1995; Vellutino et al., 1975). In support of a verbal locus of PAL deficits,

Messbauer and de Jong (2006) showed that poor visual-verbal PAL performance in children with dyslexia could be accounted for by their deficits in phonological awareness. These findings are complimented by a study by de Jong, Seveke, and van Veen (2000), in which training phonemic awareness (together with letter-sound correspondences) in kindergartners led to improvements in visual-verbal PAL, whereas training in conceptual categorization had no effect.

Other evidence, however, suggests that phonological awareness alone may not explain the PAL-reading relationship. As previously discussed, visual-verbal PAL explains unique variance in reading even after accounting for phonological awareness (Hulme et al, 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Additionally, Windfuhr and Snowling (2001) showed that in typically developing readers, visual-verbal PAL performance was only partly explained by individual differences in phonological awareness. And in contrast to the findings of Messbauer and de Jong (2006), Wimmer, Mayringer, and Landerl (1998), reported PAL deficits in children with dyslexia even when they were matched to controls for phonological awareness.

Although phonological awareness may not fully explain PAL deficits in dyslexia, it is important to remember that phonological awareness represents just one aspect of the phonological system<sup>2</sup> (Wagner & Torgesen 1987; Wagner et al., 1999). Regardless of the specific component(s) tapped by visual-verbal PAL, the evidence strongly suggests that PAL deficits in dyslexia stem from difficulties specific to the phonological, rather than the associative component of the task. For example, although children with dyslexia perform less well than controls in visual-verbal PAL, analyses of their errors shows that they do not commit more associative errors (matching the wrong

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<sup>2</sup> The difference between phonological awareness and the components of the phonological system that might be tapped by PAL will be addressed in Chapters 2-5 of this thesis

word with the wrong symbol) than controls; rather, their errors are indicative of a difficulty learning novel words (Ho et al., 2006; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003). Numerous studies provide support for the suggestion that children with dyslexia have difficulties acquiring novel (spoken) words. Aguiar and Brady (1991) investigated vocabulary acquisition in dyslexia by teaching children the names and meanings of novel objects. Children with dyslexia needed more trials to learn the names of the objects, but learned the definitions at the same rate as controls. Similarly, Elbro and Jensen (2005) showed that children with dyslexia needed more trials than controls to learn picture-novel word pairings, although they learned picture-word pairings at the same rate. Finally, Carroll and Snowling (2004) demonstrated that children at family-risk for dyslexia experience substantial difficulties learning novel phonological forms embedded in the context of a storybook. The authors suggested that deficits in phonological form learning may lead to inaccurate and less well-specified phonological representations, which in turn, may explain poor performance on a range of phonological tasks.

There is no doubt that children with dyslexia exhibit visual-verbal PAL deficits when the verbal stimuli comprise novel words; however, evidence from PAL tasks that use words rather than nonwords is more equivocal (Elbro & Jensen, 2005; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003, 2006; Vellutino et al., 1975; Vellutino, Bentley, & Phillips, 1978; Vellutino, Scanlon, & Bentley, 1983). Whether visual-verbal PAL deficits emerge for words seems to depend upon the nature of the verbal stimuli and the degree to which they tax the phonological system (e.g., de Jong et al., 2000; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003, 2006; Vellutino et al., 1995). For example, deficits are observed when stimuli comprise abstract or low frequency words, but are typically absent for concrete words, or words that are high in frequency

or imageability (Elbro & Jensen, 2005; Messbauer & de Jong, 2006; Samuels & Anderson, 1973; Vellutino et al., 1995). Such findings suggest that both the phonological demands of the stimuli (e.g. frequency, complexity) and the availability of non-phonological information (e.g. visual, semantic) influence the likelihood of observing PAL deficits in dyslexia. Vellutino and colleagues (1995) suggested that children with dyslexia rely more heavily on semantics to compensate for primary deficits in “phonological coding.” On a visual-verbal PAL task with words that were high in meaning, children with dyslexia performed as well as controls, however performance was impaired on a task with words that were low in meaning. Interestingly, similar results were found for free recall tasks in which children had to recall (auditory) lists of words that were high and low in meaning; additionally, the visual-verbal PAL task and verbal memory task were highly correlated. The authors suggested that the difficulties experienced by children with dyslexia were attributable to difficulty with the storage and retrieval of phonological forms, rather than a difficulty specific to associative learning.

### *Competing accounts of the PAL-reading relationship*

It is clear from the literature reviewed above that there are two competing accounts of the PAL-reading relationship. The *crossmodal account* proposes that visual-verbal PAL taps a crossmodal associative learning mechanism involved in the establishment of orthography-phonology mappings. In contrast, the *verbal account* suggests that visual-verbal PAL performance is dependent on verbal (output) task demands and thus reflects the integrity of the phonological system. Figure 1.1 provides a visual schematic of these two accounts. The crossmodal account views the ability to form crossmodal associations between stimulus and response items as the crucial

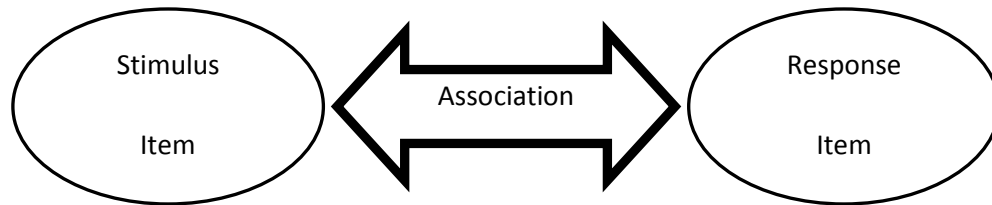
component underlying the PAL-reading relationship. Alternatively, according to the verbal account, the key component driving the PAL-reading relationship lies in the learning of a verbal response item, and thus is not specific to associative learning itself.

The two accounts of the PAL-reading relationship lead to clear, yet divergent predictions. If crossmodal associative learning drives the PAL-reading relationship, any task with a crossmodal mapping demand should demonstrate a relationship with reading, regardless of the direction of the mapping (i.e., visual-verbal, verbal-visual)<sup>3</sup>. If, on the other hand, verbal response demand drives the PAL-reading relationship, any PAL task with verbal output demand should relate to individual differences in reading ability, regardless of the modality of the input (e.g. visual, verbal) or the association (unimodal, crossmodal).

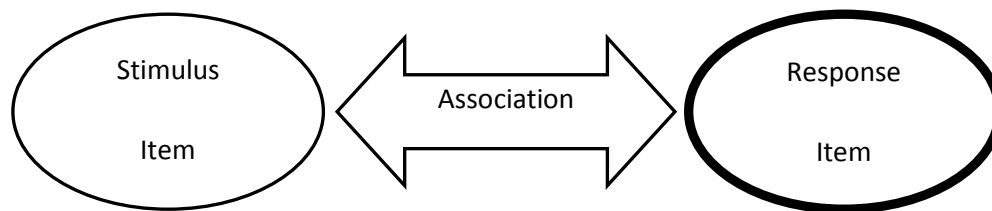
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<sup>3</sup> Although one might expect visual-verbal PAL to exhibit a stronger correlation with reading ability due to its closer approximation of reading, a strong version of the crossmodal hypothesis would receive support from the finding that verbal-visual PAL is also related to reading ability

## A. Crossmodal Account



## B. Verbal Account



*Figure 1.1.* Visual schematic depicting the component of learning hypothesized to drive the PAL-reading relationship according to a) the crossmodal and b) the verbal account

Although the predictions of the verbal and crossmodal account are clear, careful experimental design is necessary to distinguish between the accounts. The factorial design introduced by Hulme and colleagues (2007) provided the first step toward elucidating this issue. By including verbal-verbal PAL in the design, the authors were able to test whether verbal response learning alone explains the relationship between visual-verbal PAL and reading. As highlighted by the authors, it might be expected that any PAL task that places demands on the phonological system may indeed demonstrate a relationship with reading ability. If these demands are responsible for the relationship between visual-verbal PAL and reading, then one would expect verbal-verbal PAL to demonstrate a correlation with reading that is similarly strong to that of visual-verbal

PAL and reading. Crucially, however, the crossmodal account predicts that if a crossmodal mechanism is responsible for this relationship, visual-verbal PAL should show a stronger, or qualitatively different relationship with reading than verbal-verbal PAL (a unimodal task). Indeed, the authors offered support for this theory: in a path analysis with visual-verbal PAL, visual-visual PAL, verbal-verbal PAL, and phoneme deletion as predictors of reading, only visual-verbal PAL and phoneme deletion emerged as significant predictors<sup>4</sup>.

However, several issues warrant further consideration. First, both verbal-verbal and visual-verbal PAL demonstrated significant correlations with measures of word, nonword, and the irregular word reading that were similar in magnitude. Although visual-verbal PAL was the only PAL task to explain unique variance in reading ability in the path model, it is clear that verbal-verbal PAL shares a relationship with reading ability. One potential difficulty with the interpretation of these results is that the difference in the strength of the correlations between each PAL task and the reading measures, and the difference in the path weights in the path models was not directly tested. That is, although visual-verbal PAL was the only PAL task to reach significance as a unique predictor in the model, whether this path weight was significantly different from the weight from verbal-verbal PAL (or the other PAL measures) to reading was never tested. Additionally, non-significant path weights have been dropped in the simplified path models reported in the paper. Although this improved model fit, it may also have led to inflation of the path weight from visual-verbal PAL to reading via indirect effects from the other PAL tasks (which were correlated with visual-verbal PAL). The original path weights (in the saturated model) are not reported, so the strength of the path weight between verbal-verbal PAL and reading cannot be assessed.

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<sup>4</sup> Note that this pattern held for the composite reading measure and irregular word reading, but for nonword reading, only phoneme deletion emerged as a unique predictor

One might conceive of a situation in which visual-verbal PAL reached significance with a path weight that was only slightly higher than that of verbal-verbal PAL, which did not reach significance. With relatively small sample sizes, very slight differences in beta weights can make the difference between failing to reach, or reaching significance. This is of course, speculative; however, it highlights the need to test for direct differences between correlations or path weights before concluding that one variable shares a stronger relationship with an outcome variable than another variable. This is particularly important when correlated variables demonstrate similar relationships with outcome variables.

Additionally, although the results of the Hulme et al. (2007) study clearly suggest that visual-verbal PAL enjoys special status as a predictor reading ability, the design does not allow for a strong test of the crossmodal hypothesis. If the component responsible for the PAL-reading relationship indeed lies at the level of the association, then any crossmodal PAL task, regardless of the direction of the mapping, should demonstrate a relationship with reading ability. Testing this prediction is crucial to distinguishing between the verbal and crossmodal hypotheses.

### Thesis Aims and Overview

The first aim of this thesis was to distinguish between the verbal and crossmodal account of the PAL-reading relationship. To do so, we employed a fully balanced factorial design that allowed for the dissociation of crossmodal and verbal demands in driving the PAL-reading relationship. In this design, each of the PAL mapping conditions is uniquely characterized by both modality (crossmodal, unimodal) and output demand (visual, verbal): visual-verbal, verbal-verbal, visual-visual, and verbal-

visual. This novel design provided the comparisons necessary to directly test both the verbal and the crossmodal account of the PAL-reading relationship.

For the purposes of this thesis, we chose to use novel stimuli in our PAL tasks (see Appendix A). This choice was motivated by several factors. First, when using known stimuli, it is always possible that the differences observed in the experiment do not reflect experimental manipulations, but instead reflect factors outside the control of the experiment (e.g. differences in prior knowledge/experience with the stimuli). Second, as outlined above, the conflicting findings regarding PAL deficits for tasks with words may be a consequence of the stimuli utilized in each study. The use of novel stimuli is advantageous in that it allows for complete control over the properties of the stimuli and the amount of exposure each participant receives.

Chapters 2 and 3 present a series of studies that address the first aim of this thesis by systematically manipulating verbal and crossmodal task demands. Chapter 2 investigates the specificity of the PAL-reading relationship in typically developing children. This same design is utilized in Chapter 3 to examine the nature of PAL deficits in dyslexia. An additional question explored in Chapter 3 is the extent to which PAL deficits reflect phonological form learning vs. associative learning difficulties. By utilizing the same design with typically developing children and children with dyslexia, Chapters 2 and 3 also address whether the characteristics of the PAL-reading relationship hold across readers of different abilities.

The second major aim of this thesis was to investigate the causal role of PAL in reading development. Chapter 4 presents the results of a longitudinal design to assess the direction of the PAL-reading relationship. Although longitudinal studies cannot establish causality, they provide the necessary next test of a causal hypothesis following the observation of a concurrent relationship between variables. Longitudinal studies ask

whether skills measured at one time point influence the measure of interest at a later time point. In reading research, it is particularly useful to measure skills thought to be precursors of reading before children learn to read. If these skills go on to predict later reading development, this provides the first indication of a causal relationship. Of course, the best evidence for causation come from training studies in which training the ability in question leads to clear improvements in the outcome of interest. However, if a concurrent relationship fails to demonstrate a longitudinal relationship, this undermines the causal hypothesis, thus deeming training studies unnecessary.

Together, these experiments elucidate the nature of the PAL-reading relationship.

## **Chapter 2: Dissociating crossmodal and verbal demands in driving the PAL-reading relationship**

*This chapter reports an experiment designed to disassociate the role of crossmodal and verbal demand in driving the PAL-reading relationship in typically developing readers. To do so, PAL performance was compared across four mapping conditions: visual-verbal, verbal-verbal, visual-visual, and verbal-visual. We reasoned that if crossmodal mapping demand accounts for the PAL-reading relationship, both visual-verbal and verbal-visual PAL should exhibit significant relationships with reading ability. The results were incompatible with the crossmodal hypothesis. Only tasks requiring verbal output (visual-verbal, verbal-verbal PAL) significantly correlated with reading ability. Additionally, visual-verbal and verbal-verbal PAL were well represented by a latent “verbal-output PAL” factor. Structural equation modeling showed that this factor fully accounted for the PAL-reading relationship; visual-verbal PAL did not add anything to the prediction of reading above and beyond this latent factor. The results are interpreted according to the verbal account of the PAL-reading relationship.*

## Experiment 2.1

### Introduction

Two of the skills most strongly associated with reading development are phonological awareness (e.g., Melby-Lervag, Lyster & Hulme, 2012) and rapid automatized naming (RAN; e.g., Norton & Wolf, 2012). In recent years, paired associate learning (PAL) has garnered increasing interest as an additional, independent predictor of reading ability (Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Warmington & Hulme, 2012; Windfur & Snowling, 2001).

PAL involves learning arbitrary associations between stimulus (i.e., input) items and response (i.e., output) items in memory. These pairings can be unimodal (e.g., visual-visual, verbal-verbal) or crossmodal (e.g., visual-verbal) in nature. In the context of reading development, crossmodal PAL is defined as any association requiring a connection (regardless of the direction) between a visual and a verbal stimulus. Crucially, performance on any PAL task depends on successful learning of three distinct components: the stimulus item, the response item, and the association between the two. Thus, individual differences in performance may stem from processes operating at any of these three levels. Reading, especially in the early stages of development, may be classed as a form of crossmodal, visual-verbal PAL. Learning the letters of the alphabet, for example, depends on the formation of arbitrary sound-symbol associations. Letter knowledge is widely viewed as a precursor to the alphabetic principle and the extent of the child's letter knowledge is a robust predictor of reading ability (Byrne, 1998; Hulme et al., 2007; Lervåg, Bråten, & Hulme, 2009; de Jong & van der Leij, 1999; Muter et al., 2004; Schatschneider et al., 2004). Additionally, in deep orthographies such as English, the acquisition of irregular sight words may rely in part on this ability to form arbitrary orthography-to-phonology mappings (Hulme et al., 2007; Windfuhr & Snowling, 2001).

The potential involvement of visual-verbal PAL in reading fits well within a connectionist framework. In connectionist models, initially arbitrary connections between orthographic input and phonological output are strengthened through a learning algorithm that alters connection weights through repeated experience. These connection weights are viewed as analogous to the associations formed between visual and verbal stimuli in a PAL task (Hulme et al., 2007; Seidenberg & McClelland, 1989; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Importantly, varying the efficiency of this learning mechanism (by altering the rate with which connection weights are altered), or limiting its resources (by removing hidden units), results in a differential pattern of impairment than degrading the phonological representations, suggesting unique roles for these mechanisms in reading development (Harm & Seidenberg, 1999; Seidenberg & McClelland, 1989).

Consistent with this pattern of findings, studies in typically developing readers have repeatedly shown that visual-verbal PAL is independent from phonological awareness and a strong concurrent predictor of reading ability (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Similarly, although PAL and RAN correlate moderately with each other, they tap separate mechanisms involved in reading (Lervåg, Bråten, & Hulme, 2009). Warmington and Hulme (2012) reported that even after accounting for phoneme deletion and RAN, visual-verbal PAL was a significant predictor of word and nonword reading accuracy, as well as reading speed. Together, these findings suggest that visual-verbal PAL is an independent predictor of reading development, accounting for variance in both lexical and nonlexical components of reading ability.

However, the underlying mechanisms responsible for the involvement of visual-verbal PAL in reading have yet to be fully elucidated. A recent theoretical account of

the PAL-reading relationship comes from Hulme and colleagues, who proposed that visual-verbal PAL taps a crossmodal associative learning mechanism involved in establishing orthography-phonology mappings (Hulme et al., 2007; Warmington & Hulme, 2012). This crossmodal hypothesis comes from a study in which the authors compared three PAL tasks (visual-verbal, visual-visual, and verbal-verbal) to evaluate the specificity of the relationship between visual-verbal PAL and reading (Hulme et al., 2007). The inclusion of verbal-verbal PAL in the design marked a necessary step in understanding the PAL-reading relationship. In requiring verbal learning and verbal output, both visual-verbal PAL and verbal-verbal PAL tax the verbal system, whereas visual-visual PAL provides a proxy of more general associative learning abilities. Given that verbal skills, such as verbal short-term memory and phonological awareness, are strongly implicated in reading development, one would expect tasks that draw on this system to be related to reading ability (e.g., Snowling & Hulme, 1994; Vellutino et al., 2004).

Consistent with this idea, both visual-verbal and verbal-verbal PAL correlated with reading ability, whereas visual-visual PAL did not (Hulme et al., 2007). Although Hulme and colleagues noted that visual-verbal PAL appeared to have a slight edge over verbal-verbal PAL in the strength of its correlations with reading, the significance of this difference was never tested. However, visual-verbal PAL was the only PAL task to predict unique variance in reading ability above and beyond phoneme deletion and the other PAL measures. These findings were interpreted as evidence for the specific role of visual-verbal PAL in reading, leading the authors to suggest that visual-verbal PAL taps modality specific “connection forming” mechanisms, akin to those operating in connectionist models.

Despite the appeal of the crossmodal hypothesis for theories of reading development, there is an alternative account of PAL that warrants further investigation. We term this the verbal account. The basis for this account stems from findings in children with dyslexia, in which deficits in visual-verbal PAL appear to be related to the verbal nature of the task, rather than its crossmodal demands (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Vellutino et al., 1975; Vellutino et al., 1995; Wimmer et al., 1998). For example, Mayringer and Wimmer (2000) showed that children with dyslexia are impaired in visual-verbal PAL when the verbal stimuli comprise nonwords, but not when they comprise short, familiar words. In Vellutino et al.'s (1975) study, children learned two crossmodal associations: visual-verbal and visual-auditory (termed "nonverbal"). The first required an association between a visual symbol and a nonword, whereas the latter required an association between a visual symbol and a nonverbal oral sound (e.g., humming, coughing, puckering lips). Although both experimental conditions required a crossmodal association, as well as oral production, children with dyslexia exhibited impairment only in visual-verbal PAL. Thus, the dyslexia literature is strongly suggestive of a primary difficulty with the verbal component of visual-verbal PAL rather than the formation of crossmodal associations. Indeed, many researchers have proposed that verbal learning is the crucial component of visual-verbal PAL, because the most robust deficits are observed for nonword stimuli (Elbro & Jensen, 2005; Mayringer & Wimmer, 2000; Vellutino et al., 1975). But what role might verbal learning play in reading development?

Although children come to the task of reading with established phonological representations (formed through oral language experience), the acquisition of novel phonological forms (i.e. new vocabulary) continues via written language experience once the child is literate. In addition to this more obvious case of verbal learning, recent

evidence suggests that the process of learning to read requires the acquisition of a less intuitive class of novel phonological representations (Elbro & Jensen, 2005; Elbro, de Jong, Houter, & Nielsen, 2012; Ranbom & Connine, 2011; Tunmer & Chapman, 2011). These representations can be seen as orthographically derived (resulting from written rather than oral language experience) (Ranbom & Connine, 2011). Consider the following illustration: when a child encounters an irregular word such as *yacht* for the first time, he or she will attempt to decode it using grapheme-phoneme correspondence rules. The first attempt (and likely several subsequent attempts) will inevitably lead to an incorrect pronunciation "y-a-**ch**-t." Here, the pronunciation derived from the decoding attempt clearly differs from the spoken pronunciation. So how does a child learn that "yacht" is in fact "yot"?

One suggestion is that the spelling pronunciation (the pronunciation generated via phonological recoding) becomes linked to the phonological representation of the spoken word (Elbro et al., 2012; Ranbom & Connine, 2011; Tunmer & Chapman, 2011). This process, akin to verbal-verbal PAL, allows the novice reader to utilize the product of phonological recoding to arrive at the correct spoken word representation. Evidence for this comes from Elbro et al., (2012), who found that children's ability to recognize words from spelling pronunciations accounted for unique variance in reading ability, even after controlling for phoneme deletion, RAN, and vocabulary. This skill was equally important for regular and irregular word reading, which was explained by the fact that for beginning readers, the product of a decoding attempt may be quite far from the spoken form, even for regular words (e.g., "cuuh...aaa..tuuh" is not equivalent to "cat"). Thus the acquisition of novel phonological representations may be a general requirement of learning to read. It is this verbal learning ability that may in fact be indexed by visual-verbal PAL.

Clearly, there is an alternative theoretical framework from which to interpret the PAL-reading relationship. The aim of the current study was to directly evaluate the crossmodal and verbal accounts of the PAL-reading relationship by dissociating the role of modality and verbal demands. To do so, we included four PAL conditions: visual-verbal, verbal-verbal, visual-visual, and verbal-visual. The novel crossmodal condition, verbal-visual PAL, was included for two reasons. First, it allowed for a fully balanced design in which each of the four mapping conditions is uniquely characterized by both modality (crossmodal, unimodal) and output demand (visual, verbal). This provided the comparisons necessary to directly test both the crossmodal account and the alternative verbal account of the PAL-reading relationship. Second, although Hulme and colleagues' (2007) theory does not specifically address mapping direction, its focus on the level of the association (rather than stimulus-specific or response-specific learning) naturally leads to the prediction that any task requiring an association between a visual and verbal stimulus should be involved in reading development. The addition of verbal-visual PAL to our design therefore addressed the prediction that both crossmodal tasks should correlate with reading, regardless of the direction of the mapping.

We hypothesized that if crossmodal associative learning is the primary mechanism underlying the PAL-reading relationship, both visual-verbal PAL and verbal-visual PAL should demonstrate strong predictive relationships with reading, independent of the effects of phoneme deletion and RAN. Crucially, although one might expect differences in the *strength* of the relationship as a function of task similarity (e.g., mapping direction is the same for visual-verbal PAL and reading, but different for verbal-visual PAL and reading), mapping direction should not fundamentally determine the PAL-reading relationship. Instead, the shared “crossmodal” component of visual-verbal and verbal-visual PAL (as tapped by a latent

variable) should fully account for the PAL-reading relationship. On the other hand, if verbal demand drives the PAL-reading relationship, both visual-verbal PAL and verbal-verbal PAL should show strong predictive relationships with reading, independent of the effects of phoneme deletion and RAN. Additionally, the shared “verbal output” component of visual-verbal and verbal-verbal PAL (as tapped by a latent variable) should fully account for the PAL-reading relationship.

## **Method**

### **Participants**

Sixty-four children (30 male, 34 female) ranging in age from 7 years, 9 months to 11 years, 9 months ( $M = 9$  years, 7 months;  $SD = 9.30$  months) were recruited from three state primary schools serving socially-mixed catchment areas in Oxfordshire, UK. All children scored within average range (T score between 40 and 60) on the Matrix Reasoning subtest from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999).

### **Design**

Children were tested in five sessions across a five-week period. In week one, children completed tests of nonverbal reasoning, reading ability, phonological awareness, and rapid automatized naming. In sessions 2-5 children completed each of the four PAL mapping conditions. One condition was tested per week to minimize interference between conditions and the order in which children completed the conditions was counterbalanced.

## Materials and Procedure

**Reading and reading-related skills.** The following standardized assessments were made with the tests administered according to the test manual instructions.

*Single Word Reading.* The Single Word Reading Test (SWRT) 6-16 was administered as a measure of untimed single word reading ability (Foster, 2007). Children are instructed to read aloud as many words as possible, starting at the top of the page. There is no time limit on this test.

*Word Reading Fluency.* The Sight Word Efficiency subtest from the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) was used as a measure of sight word reading. The raw score is defined as the total number of words (out of 104) that can be read correctly in 45 seconds.

*Nonword Reading Fluency.* The Phonemic Decoding Efficiency subtest from the TOWRE (Torgesen et al., 1999) was used as a measure of speeded nonword reading. The raw score is the total number of nonwords read correctly in 45 seconds.

*Phoneme Deletion.* The Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999) assessed phonological awareness (PA). Participants are asked to delete single phonemes from words (e.g., “Say *bold* without the *b*”).

*Rapid Automatized Naming.* The rapid digit naming subtest of the CTOPP was administered as an assessment of RAN. Six digits (e.g., 4, 7, 8, 5, 2, 3) are repeated six times throughout a 36-item matrix arranged in four rows of nine items. Children must name the items in the matrix sequentially, starting at the top of the page from left to right as quickly as possible until they have named all 36 items. Children complete two separate arrays that differ only in the order the digits are presented. The time (in

seconds) taken to name the items in each array is summed to produce a total naming score.

**Paired associate learning.** All children completed four PAL mapping conditions: visual-verbal, verbal-verbal, visual-visual, and verbal-visual. For each condition they learned six stimulus-response pairs comprised of sets of verbal and/or visual stimuli. The stimulus-response pairs were fixed, such that all children learned the same pairings. The presentation of the stimulus-response pairs was randomized for each trial. Stimulus-response pairs for each condition can be found in Appendix A.

*Visual Stimuli.* The abstract symbols within each PAL condition were chosen from extinct written languages (e.g., Akkadian) and matched across conditions for difficulty of verbalization. These data were obtained from testing in which 15 adults were asked to rate 54 potential stimulus items on a scale of 1-10 (with 10 being most difficult) for degree of verbalization (i.e., “how easy is it to assign a verbal label or description to this item?”), and ease of drawing (i.e., “how easy is it to draw this item?”). The 24 symbols hardest to verbalize were assigned to four sets (i.e., two sets of stimulus items, and two sets of response items) that comprised the visual stimuli for the PAL conditions. The visual stimuli were matched for ease of verbalization across the four sets,  $F(3, 42) = 2.11, p = .114$ . Additionally, we ensured that the two sets comprising visual response items were matched for ease of drawing,  $F(1, 14) = 1.26, p = .280$ .

*Verbal Stimuli.* The verbal stimuli comprised nonwords, all phonotactically legal CVC strings, chosen from the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002). Each of the short vowel sounds (i.e., a, e, i, o, u) and one long vowel sound (e.g., ee) were used once per stimuli set. Additionally, no two items shared

consonant positioning (i.e., first or last sound) within a stimuli set in an effort to minimize phonological similarity between items.

*PAL Procedure.* Children were tested individually in a quiet room in their school. The experiment was run using EPrime Version 2.0 presented on a Dell laptop. In each condition, the six stimulus-response pairs were presented in two presentation trials before the test trials began. In the first presentation trial, children were instructed to repeat the response item after each presentation to ensure that the responses could be accurately reproduced. For verbal response items, children were instructed to repeat each nonword aloud; for visual response items, children were instructed to draw the abstract symbol inside a booklet of blank index cards, one item per page to prevent them from referring to previous responses throughout a trial. Rarely (< 5% of first presentation to a response item), a nonword or symbol was reproduced incorrectly. In this case, the experimenter corrected the child by saying “that’s not quite right,” and then proceeded to repeat the correct nonword or draw the correct response in the booklet. In the second presentation trial the children were asked to focus on learning the pairs of items and not to reproduce the response item (following pilot testing in which instructing participants to focus on the stimulus-response pairings resulted in better learning than instructing them to reproduce the response items).

Five blocks of learning trials followed the presentation trials. Each block consisted of six trials, one for each stimulus-response pair. In each trial, the stimulus item was presented on the computer and the participant was then asked to provide the appropriate response (e.g., “What goes with hib?”). Depending on the output required, the child either drew the symbol in the booklet or verbally produced the nonword that corresponded to the stimulus item. Regardless of the accuracy of the response, the correct answer was presented on the computer immediately following each trial. This

procedure was repeated for each trial across all five blocks. All participants completed all trials, and accuracy per trial and total learning across trials was recorded. The final score was calculated as the total number of correct trials across all five blocks (maximum score of 30). The reliability of PAL tasks will be addressed in detail in Chapters 4 and 5. Cronbach's alpha for the mapping conditions in this experiment can be found in Table 5.1 (Chapter 5).

### **Results**

The children performed at an average level for reading, phonological awareness and RAN, according to population norms (see Table 2.1). The scores of two children (one for visual-verbal PAL and one for verbal-verbal PAL) were excluded pairwise from all analyses, as the scores were  $> 4 SDs$  above the sample mean. Excluding these values did not alter the pattern of results. Although visual-verbal PAL and verbal-verbal PAL demonstrated slight positive skewness, the score distributions for all measures were normally distributed.

Table 2.1

*Means (and standard deviations) for measures of PAL, phoneme awareness, RAN, and reading*

	Mean	SD	Range
Phoneme Deletion <sup>a</sup>	9.78	2.81	5-15
RAN Digits <sup>a</sup>	9.95	2.51	6-15
TOWRE Sight Word Efficiency <sup>b</sup>	104.67	11.59	76-133
TOWRE Nonword Efficiency <sup>b</sup>	104.33	14.01	74-139
Single Word Reading Test <sup>b</sup>	96.84	13.59	69-129
Visual-verbal PAL <sup>c</sup>	5.84	5.22	0-27
Verbal-verbal PAL <sup>c</sup>	4.86	4.62	0-25
Visual-visual PAL <sup>c</sup>	9.98	4.72	1-20
Verbal-visual PAL <sup>c</sup>	11.61	5.40	3-25

*Notes.* <sup>a</sup>Scaled score,  $M = 10$ ,  $SD = 3$ ; <sup>b</sup>Standard score,  $M = 100$ ,  $SD = 15$ ; <sup>c</sup>Raw score, max = 30

As indicated by the relatively modest mean scores across PAL conditions, the children found the PAL tasks quite challenging. Nevertheless, it is clear that our tasks captured a wide range of performance across all four PAL conditions. A repeated-measures analysis of variance showed that performance varied significantly across PAL conditions,  $F = 40.70$ ,  $p < .001$ ,  $\eta_p^2 = .39$ . Planned pairwise comparisons (with Bonferroni correction) revealed two interesting findings. First, there were no significant differences between conditions with the same output demand. That is, there were no significant differences between the two verbal output conditions, visual-verbal PAL and verbal-verbal PAL,  $p = .639$ , and no significant differences between the visual output conditions, verbal-visual and visual-visual PAL,  $p = .198$ . Second, comparisons within

modality revealed a significant difference between the crossmodal conditions (visual-verbal, verbal-visual),  $p < .001$ , as well as a significant difference between the unimodal conditions (verbal-verbal, visual-visual),  $p < .001$ . In both of these comparisons, performance was lowest in the condition requiring verbal output. Thus, performance differences appear to be driven by the increased difficulty of the two verbal output conditions.

#### *Relationship between PAL and reading measures*

Table 2.2 displays the simple correlations (above the diagonal) and partial correlations controlling for age (below the diagonal) among measures. The age-controlled correlations are slightly lower than the simple correlations, but show the same overall patterns. As there was no difference in the pattern of correlations, we focus here on the age-controlled correlations.

Table 2.2

*Correlations among PAL, RAN, and reading measures (simple correlations above the diagonal, partial correlations controlling for age below the diagonal)*

	1	2	3	4	5	6	7	8	9
1. Phoneme Deletion		-.29*	.45**	.52**	.62*	.31*	.31*	.14	.25*
2. RAN	-.18		-.70**	-.67**	-.56**	-.14	-.26	-.16	-.20
3. Sight Word Fluency	.36**	-.61**		.79**	.74**	.33**	.30*	.10	.21
4. Nonword Fluency	.47**	-.63**	.77**		.71**	.32*	.30*	.13	.15
5. Word Reading Accuracy	.58**	-.45**	.67**	.68**		.39**	.42**	.13	.17
6. Visual-Verbal PAL	.28*	-.05	.27*	.27*	.34**		.45**	.31*	.33**
7. Verbal-Verbal PAL	.26*	-.20	.23	.25*	.37**	.42**		.41**	.34**
8. Visual-Visual PAL	.12	-.13	.07	.10	.10	.29*	.40**		.31
9. Verbal-Visual PAL	.19	-.10	.10	.08	.06	.29*	.30*	.30*	

Notes. \* p < .05. \*\* p < .01.

As expected, the reading measures correlated highly with each other. Performance across the four PAL conditions was moderately correlated ( $r = .29-.42$ ). The pattern of the correlations between the PAL tasks and reading is striking: only visual-verbal PAL and verbal-verbal PAL demonstrate significant correlations with reading. In contrast, visual-visual PAL and verbal-visual PAL demonstrate a clear lack of relationship with reading. The pattern of correlations indicates that verbal output, rather than crossmodal mapping, is a necessary component of the PAL-reading relationship—the verbal output PAL measures (visual-verbal, verbal-verbal) show similar and significant correlations with all three measures of reading (word fluency, nonword fluency, word accuracy), whereas the visual output PAL measures (visual-visual, verbal-visual) show nonsignificant correlations with all three measures.

#### *Modeling the relationship between PAL, phoneme deletion, RAN, and reading*

Our next set of analyses addressed whether performance on the PAL tasks was associated with unique variance in reading, beyond the variance accounted for by phoneme awareness and RAN. We utilized maximum likelihood estimation techniques to conduct a series of path analyses using MPlus (version 5.21, Muthén & Muthén, 2009). All raw scores on measures were residualized for age before running the analyses to enable the examination of age-independent relationships. To establish the strength of each task on its own as a predictor of reading, four separate models were constructed, one for each PAL task (Figure 2.1); including all tasks in the same model might have led to potential path inflation due to suppression effects, given the correlation between the PAL measures. The models allowed for correlations between predictors and all possible paths from the predictors (PAL, phoneme deletion and RAN) to reading (word accuracy, word fluency and nonword fluency).

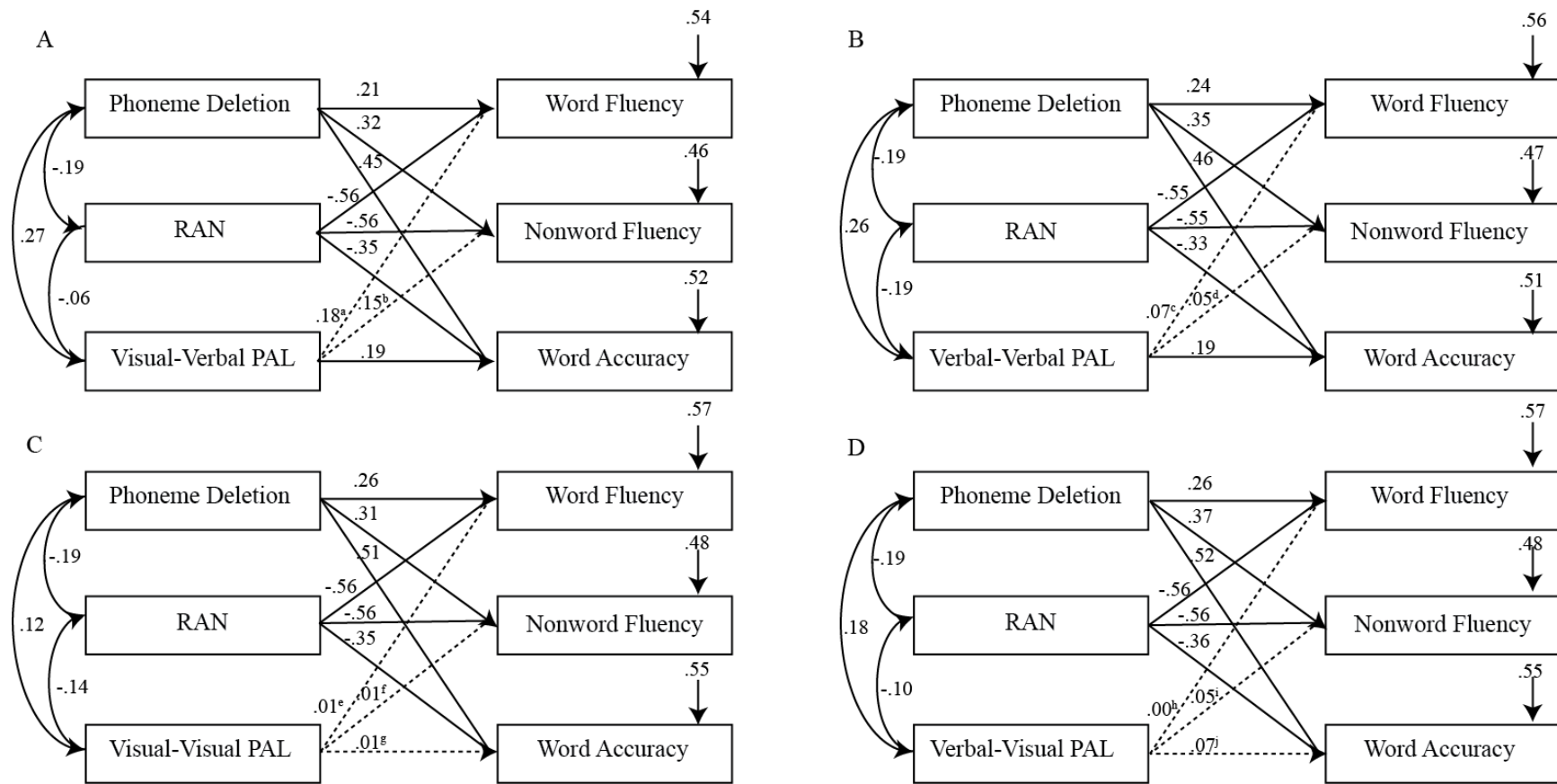


Figure 2.1. Path analysis models predicting word reading fluency, nonword reading fluency, and word reading accuracy from phoneme deletion, RAN, and (A) visual-verbal PAL, (B) verbal-verbal PAL, (C) verbal-visual PAL, or (D) visual-visual PAL. Solid arrows represent statistically significant predictive relationships. Dashed arrows represent non-significant predictive relationship: (a)  $p = .059$ , (b)  $p = .086$ , (c)  $p = .498$ , (d)  $p = .459$ , (e)  $p = .981$ , (f)  $p = .595$ , (g)  $p = .466$ , (h)  $p = .665$ , (i)  $p = .872$ , (j)  $p = .907$ . Double-headed arrows represent correlations between predictors. The arrows and values above the dependent variables represent the proportion of variance not explained by the predictors in the model, or the residual variance. All values presented in the model are standardized values.

Unsurprisingly, the paths from phoneme deletion and RAN to all three reading measures were significant in all models. In accordance with the verbal account of the PAL-reading relationship, both visual-verbal PAL (panel A) and verbal-verbal PAL (panel B) predicted significant unique variance in word reading accuracy. In contrast, visual-visual PAL (panel C) and verbal-visual PAL (panel D) did not contribute to the prediction of reading ability above and beyond phoneme deletion and RAN. Given the demonstrated lack of relationship with reading ability, these visual-output PAL tasks will not be considered in further analyses.

The similarity of the verbal-output PAL models is striking; both PAL measures predicted significant unique variance in word reading accuracy only, whereas phoneme deletion and RAN predicted unique variance in all three reading measures. However, although the structure of the models is identical, it is worth noting that the path weights from visual-verbal PAL to word and nonword fluency are marginal, and larger than those from verbal-verbal PAL to fluency measures. This may be suggestive of a difference in the strength of the verbal-output PAL tasks as predictors. If visual-verbal PAL makes a contribution to the prediction of reading fluency that cannot be accounted for by the verbal output component of the task, it would be inconsistent with a purely verbal account of the PAL-reading relationship.

#### *Examining the specificity of the PAL-reading relationship*

Having demonstrated that the PAL-reading relationship holds only for verbal output PAL tasks, we next evaluated whether this relationship can be fully accounted for by the shared component of the tasks. Additionally, we examined whether this shared “verbal-output PAL” component accounted for unique variance in reading, after controlling for phoneme awareness and RAN. We started by running a confirmatory

factor analysis (CFA) with three factors: verbal-output PAL, phoneme deletion, and RAN. Our primary aim was to examine whether visual-verbal PAL and verbal-verbal PAL can be represented by an underlying latent factor, “verbal-output PAL.” For the proper comparison of possible differences in the relationships between PAL, phoneme deletion, and RAN, we also specified latent variables for phoneme deletion and RAN. Doing so allowed us to account for differences in reliability between the tasks. To form latent factors for phoneme deletion and RAN, the overall scores were split into two sets of scores to be used as indicators. For phoneme deletion, scores were split into total number correct on odd and even test items. For RAN, we used the two subtests that comprised the total RAN score as indicators. This method resulted in two indicators for each latent variable. We ran a confirmatory factor analysis (CFA) with three factors: verbal-output PAL, phoneme deletion, and RAN. To aid in local identification, the indicators for each latent variable were specified with equal factor loadings. The results of the CFA indicated that a three-factor model fitted the data well,  $\chi^2(9) = 7.18, p = .619, RMSEA = .000$  [90% CI: .000-.119], SRMR = .04, CFI = 1.00. The factor loadings for verbal-output PAL (.67), phoneme deletion (.93), and RAN (.94), were all significant at the  $\alpha = .01$  level (Stevens, 2009).

Having confirmed that visual-verbal PAL and verbal-verbal PAL are well represented by an underlying latent variable, we next constructed a structural equation model<sup>5</sup> with the three latent variables as predictors of word fluency, nonword fluency, and word accuracy. The model (Figure 2.2) provided an excellent fit to the data,  $\chi^2(18) = 18.64, p = .415, RMSEA = .024$  [90% CI: .000-.115], SRMR = .03, CFI = .998.

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<sup>5</sup> Structural equation modeling (SEM) is often used to determine the fit of a full causal model to the data, thus requiring a large sample size to ensure adequate power. However, in the current study SEM was used to perform multivariate multiple regression using latent independent variables. This is akin to multiple regression analyses in which one coefficient is tested to deviate significant from zero. In such analyses, a sample size of 64 is generally considered adequate to reject the null-hypothesis.

Verbal-output PAL accounted for unique variance only in reading accuracy, whereas phoneme deletion and RAN accounted for unique variance in all three reading measures. Together, the latent variables accounted for 50% of the variance in word reading fluency, 58% of the variance in nonword reading fluency, and 53% of the variance in word reading accuracy.

To test whether visual-verbal PAL shares an additional and specific relationship with reading that cannot be accounted for by the latent construct (i.e., the shared component of visual-verbal PAL and verbal-verbal PAL) we ran the model with an added direct path from visual-verbal PAL to each of the reading measures (in separate iterations). The added direct effects did not result in significant improvement to model fit (word fluency,  $\Delta\chi^2(1) = .71, p = .399$ ; nonword fluency,  $\Delta\chi^2(1) = 1.03, p = .310$ ; word accuracy,  $\Delta\chi^2(1) = .61, p = .435$ ). Thus, visual-verbal PAL did not account for variance in reading ability above that explained by the shared variance with verbal-verbal PAL.

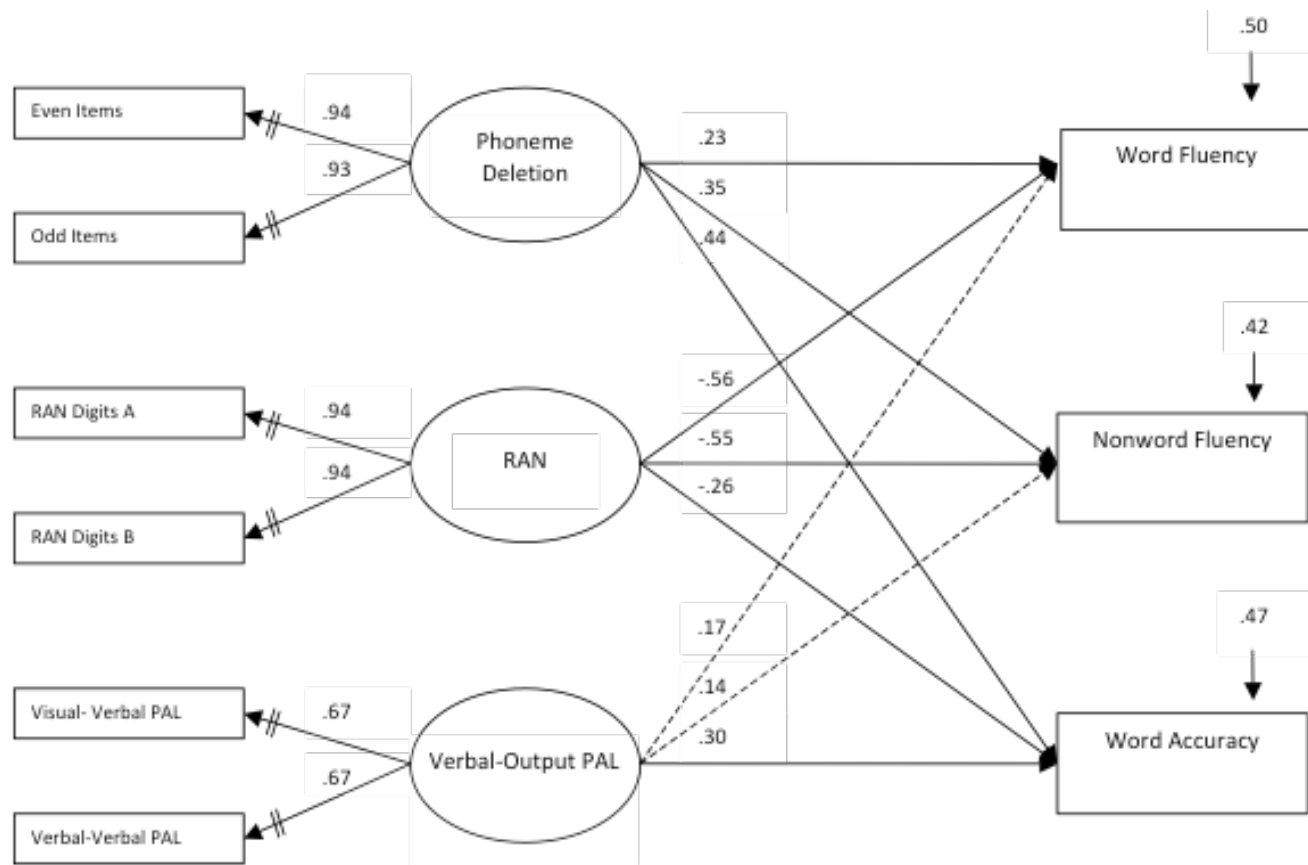


Figure 2.2. Structural equation model of the relationship between the latent cognitive constructs and reading ability. Circles represent latent variables. Rectangles to the left of the diagram represent observed indicators for the latent variables, and rectangles to the right of the diagram represent observed dependent variables. Solid arrows represent statistically significant predictive relationships. Dashed arrows represent non-significant predictive relationships. Parallel lines indicate that the paths were constrained to be equal. The arrows and values above the dependent variables represent the proportion of variance not explained by the predictors in the model, or the residual variance. All values presented in the model are standardized values.

Finally, we ran a series of constraints on the model to examine the differential importance of each latent variable to the prediction of fluency compared with accuracy. Constraining RAN to make equal contributions to word and nonword fluency did not affect model fit,  $\Delta\chi^2(1) = .00, p = 1.00$ , indicating that it is an equally strong predictor of both fluency measures. In contrast, additionally constraining the fluency measures to be equal to accuracy resulted in significantly poorer model fit,  $\Delta\chi^2(1) = 10.16, p = .001$ , indicating that RAN makes a stronger contribution to fluency than accuracy. For phoneme deletion, model fit was not significantly affected by imposing constraints on word and nonword fluency,  $\Delta\chi^2(1) = 1.34, p = .247$ , or by the subsequent constraint between fluency and accuracy,  $\Delta\chi^2(1) = 1.91, p = .16$ . Finally, for verbal-output PAL, model fit was not significantly affected by constraining word and nonword fluency to be equal,  $\Delta\chi^2(1) = .04, p = .842$ , or by the additional constraint between fluency and accuracy,  $\Delta\chi^2(1) = 1.26, p = .262$ .

### **Discussion**

The primary aim of this experiment was to evaluate the crossmodal account of the PAL-reading relationship. We examined performance across four PAL mapping conditions designed to dissociate the role of modality and verbal demands in determining the PAL-reading relationship. In line with Hulme et al. (2007) we found that both visual-verbal and verbal-verbal PAL correlated significantly with reading and phoneme deletion. Not surprisingly, visual-visual PAL was unrelated to reading ability; neither though was there a relationship between verbal-visual PAL and reading. This latter finding in regard to verbal-visual PAL is incompatible with the crossmodal hypothesis. Both visual-verbal and verbal-visual PAL required the crossmodal associations implied by Hulme and colleagues (2007) to drive the PAL-reading

relationship, yet verbal-visual PAL was unrelated to reading ability. Instead, the results favored the alternative verbal account that the PAL-reading relationship is driven by mechanisms specifically involved in learning, accessing, and producing verbal material.

Before accepting this conclusion we need to ask whether the failure to detect a relationship between verbal-visual PAL and reading resulted from differences between the crossmodal tasks. Although there were differences in performance levels between conditions, we find it difficult to argue that verbal-visual PAL did not adequately tap crossmodal mapping mechanisms, or that the two crossmodal PAL tasks tapped these mechanisms in different ways. First, whereas low performance levels on visual-verbal PAL may signal concerns about task difficulty, performance levels on verbal-visual PAL (see Table 2.1) were ideal. Additionally, the range of scores on the tasks were essentially the same (visual-verbal: 0-27; verbal-visual: 3-25), so it cannot be argued that either task failed to capture the full range of performance necessary to detect a relationship with reading. Finally, performance was lower in both verbal output PAL conditions compared to visual output PAL conditions. Thus, the difference in performance levels between the crossmodal tasks was likely due to the targeted differences in verbal demand, rather than unintentional differences in crossmodal demand. One might even say that verbal-visual PAL, with its lesser demands on verbal output, provided a purer index of crossmodal associative learning. It is therefore unlikely that this task would fail to correlate with reading skill if in fact crossmodal mapping ability drives the PAL-reading relationship.

Having demonstrated that the verbal-output PAL tasks show a similar pattern of correlations with reading, we next addressed the two remaining criteria for acceptance of our verbal hypothesis. First, consistent with previous research, we found that visual-verbal PAL predicted significant variance in reading accuracy, above and beyond

phoneme deletion and RAN (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Crucially, however, this finding also held for verbal-verbal PAL. Both tasks predicted significant variance in accuracy, but failed to reach significance for fluency. Although visual-verbal PAL showed a slightly stronger relationship with reading fluency than verbal-verbal PAL, this difference in relationship was not significant.

Second, in the latent model summarized in Figure 2.2, visual-verbal and verbal-verbal PAL were well represented by an underlying latent construct and, importantly, this construct fully accounted for the relationship between both PAL tasks and reading ability. That is, there was no evidence that visual-verbal PAL predicted extra variance in any of the reading measures once the latent construct was accounted for in the model.

This finding differs from that of Hulme and colleagues (2007). Whereas the pattern and strength of the specific correlations with the reading measures were largely equivocal in the current study, visual-verbal PAL exhibited slightly stronger (but not entirely systematic) correlations than verbal-verbal PAL in Hulme et al.'s (2007) study. Although the reasons for these differences are not entirely clear (perhaps due to differences in task reliability or administration procedures), it is unlikely to be due to the crossmodal demands of the task: verbal-visual PAL was unrelated to reading ability in the current study. Additionally, verbal-output PAL predicted unique variance in reading ability after controlling for the robust contribution of phoneme deletion and RAN, a finding that is consistent with the literature on visual-verbal PAL (Hulme et al., 2007; Warmington & Hulme, 2011; Windfuhr & Snowling, 2001). The fact that this finding held for our latent construct strongly suggests that verbal demand, rather than crossmodal demand, is responsible for the PAL-reading relationship. The latent construct necessarily accounted only for the verbal demands shared by visual-verbal and

verbal-verbal PAL, thus we would not expect the results of our study to replicate those cited above if crossmodal demands were essential to the PAL-reading relationship.

Therefore, we believe that we have strong evidence to assert that verbal demands drive the PAL-reading relationship.

How, then, should we conceive of the verbal demands of the tasks? What does verbal-output PAL measure and why is it related to reading ability? In line with previous research, the children in our sample did not exhibit varied performance in the immediate repetition of the nonwords (Mayringer & Wimmer, 2000). This strongly indicates that individual differences in learning the paired associates arose not from immediate perceptual or working memory processes, but from later stages of processing involved in encoding, storage, retrieval, and /or output.

One possible explanation for our findings is that both reading and verbal-output PAL depend upon successful access and retrieval of a phonological form. Consistent with this, studies have implicated deficient output processes in dyslexia (e.g., Elbro, 1998; Nation, Marshall, & Snowling, 2001; Ramus & Szenkovits, 2008; Snowling & Hulme, 1994; Swan & Goswami, 1997; Truman & Hennessey, 2006). Such difficulties are typically only apparent for tasks in which the verbal system is sufficiently taxed and explicit access and output required (see Ramus & Szenkovits, 2008). For example, children with dyslexia exhibit picture naming deficits when the stimuli comprise long, phonologically complex words, or words that are low in frequency, but not when they comprise short, high-frequency words (Swan & Goswami, 1997; Nation et al., 2001). Although verbal-output PAL tasks clearly place strong explicit output demands on the verbal system, the fact that our stimuli comprised nonwords proves difficult for this explanation. Arguably, the processes involved in the access and retrieval of words from

long-term memory differ from those utilized for recently learned nonwords (e.g., Davis, Di Betta, Macdonald, & Gaskell, 2008; Dumay & Gaskell, 2007).

Instead, it is likely that the verbal demands indexed by our PAL measures hinge critically on a skill inherent to nonword tasks: verbal learning. In line with this view, the most robust relationships with reading ability have been consistently observed in PAL tasks with nonword stimuli (Elbro & Jensen, 2005; Hulme et al., 2007; Mayringer & Wimmer, 2000; Vellutino et al., 1975). As outlined in the introduction, the role of verbal learning in reading development is supported by emerging evidence that novel phonological representations (i.e., spelling pronunciations) are generated through phonological recoding and subsequently utilized in word recognition (Elbro, et al., 2012; Ranbom & Connine, 2011; Tunmer & Chapman, 2011). According to this framework, the relationship between verbal-output PAL and reading ability may be explained by the common demand on verbal learning.

In support of this view, the pattern of relationships between verbal-output PAL and reading accuracy and fluency parallels the findings of Elbro et al. (2012), in which word recognition from spelling pronunciations better accounted for individual differences in reading accuracy than fluency. If spelling pronunciations aid in the arrival at the correct spoken representation in the lexicon, it follows that it is the *ability* to learn these pronunciations and utilize them in word recognition that determines success. In other words, so long as the spelling pronunciation cues the selection of the correct word, the efficiency with which one arrives at the word is irrelevant. Thus, we might expect a stronger relationship with reading accuracy than fluency, because fluency measures are compounded by both accuracy and speed (the latter being unnecessary for verbal learning).

However we caution against the over-interpretation of our results regarding accuracy and fluency. Verbal-output PAL only reached significance as a predictor of accuracy, but the difference in the variance explained by verbal-output PAL in reading fluency vs. accuracy was not statistically significant. Further investigation of the relationship between verbal-output PAL and measures of fluency and accuracy is therefore warranted.

Finally, it is important to consider whether verbal learning might be more distally related to reading ability, rather than playing a more integral or direct role. For example, it may be that performance on verbal-output PAL is a reflection of the level of support available from existing orthographic knowledge to support verbal learning. On this view, more skilled readers might be better able to learn new phonological forms in a verbal-output PAL task due to orthographic information being activated automatically, even though the tasks do not involve orthographic knowledge directly (e.g., Metsala, 1997; Nation & Hulme, 2011; Ricketts, Bishop & Nation, 2009). In line with this, Lervåg et al. (2009) found that visual-verbal PAL did not emerge as a longitudinal predictor of reading skill when measured in pre-readers. Additionally, children with more precise and segmented phonological representations may be better able to form novel phonological representations and can thus more easily attach these forms to orthographic information (de Jong et al., 2000; Messbauer & de Jong, 2003). Taken together, these findings suggest that verbal learning ability (as indexed by PAL) may be a consequence, rather than a cause, of reading development. However, the current data do not allow us to speak to this issue; additional longitudinal and cross-sectional studies are needed to disentangle the causal and reciprocal relationships between verbal-output PAL and reading development.

In summary, the results of the present study add to a growing body of research indicating that the PAL-reading relationship is both robust, and independent from phoneme deletion and RAN. Additionally, our results shed new light on the locus of the PAL-reading relationship by disentangling the role of crossmodal and verbal demands. Contrary to the predictions of the crossmodal hypothesis, we found that the PAL-reading relationship is not specific to visual-verbal PAL, but instead, emerges for PAL tasks with a verbal output component.

### **Chapter 3: Elucidating PAL deficits in children with dyslexia**

*This chapter reports three experiments examining the locus and specificity of PAL deficits in children with dyslexia. Experiment 3.1 investigated the specificity of PAL deficits by dissociating crossmodal and verbal demands using the factorial design introduced in Chapter 2. Children with dyslexia and age-matched controls were compared across the following mapping conditions: visual-verbal, verbal-verbal, visual-visual, and verbal-visual PAL. Children with dyslexia exhibited selective deficits in visual-verbal and verbal-verbal PAL, but performed as well as their peers in verbal-visual and visual-visual PAL. Experiment 3.2 replicated and extended these findings in a different sample of children with dyslexia and controls. The results showed that PAL deficits are driven by verbal, rather than crossmodal demands. Experiment 3.3 investigated whether PAL deficits reflect difficulties in the verbal learning or associative learning stage of the task. Children with dyslexia and age-matched controls were tested across two days. On day one, children were pre-exposed to the phonological forms in a nonword learning task. On day two, children learned to pair the same nonwords with visual forms in a visual-verbal PAL task. Results revealed an item-specific relationship between nonword learning and later associative learning success. Furthermore, associative learning deficits were fully accounted for by preceding verbal learning deficits. Together these experiments extended the findings of Chapter 2 by showing that in both unselected and selected samples of readers, only verbal-output PAL tasks demonstrate a relationship with reading ability. Additionally, the findings indicate that PAL deficits in dyslexia are not a consequence of difficulties with associative learning; instead, they are best characterized as deficits in phonological form learning.*

## Introduction

Paired associated learning (PAL) is thought to tap basic associative learning mechanisms by requiring the pairing of a stimulus and response item in memory. Evidence suggests, however, that not all PAL tasks are created equal when it comes to the relationship with reading ability. Decades of research have documented visual-verbal PAL (i.e., pairing a visually-presented symbol with a verbal output, normally a nonword) deficits in children with dyslexia, despite age-appropriate performance in nonverbal tasks such as visual-visual PAL (i.e., pairing a visually-presented symbol with another visually presented symbol) (Lieberman, Mann, Shankweiler, & Werfman, 1982; Messbauer & de Jong, 2003; Rapala & Brady, 1990; Vellutino et al., 1975; Vellutino et al., 1973). This reliable pattern of PAL deficits in dyslexia is observed across languages, despite variations in orthographic, phonological, and morphological complexity (Li et al., 2009; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003). Indeed, across the range of abilities, visual-verbal PAL shares a robust and specific relationship with reading skill (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001).

In the dyslexia literature, visual-verbal PAL deficits have typically been interpreted within the phonological deficit hypothesis of dyslexia (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Messbauer & de Jong, 2006; Vellutino et al., 1973; Vellutino et al., 1975; Vellutino et al., 1995). This prominent theory views difficulties in phonological processing as the primary cognitive-level cause of dyslexia (e.g. Fowler, 1991; Snowling, 1995; Snowling & Hulme, 1994). Difficulties with phonological processing can give rise to deficits on any task that places demands on the phonological system, including phonological awareness, verbal short term memory, speech perception and production, naming, and of course, reading and spelling. The

finding of visual-verbal PAL deficits in children with dyslexia, in the absence of visual-visual PAL deficits, fits comfortably within this framework (Messbauer & de Jong, 2003; Vellutino et al., 1973; Vellutino et al., 1975).

Evidence for the phonological nature of PAL deficits comes from the finding that the errors produced by children with dyslexia are more likely to be phonological, rather than associative in nature (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003). Additionally, differences between dyslexic and control groups in visual-verbal PAL can largely be accounted for by differences in phonological processing skills (Messbauer & de Jong, 2003; Messbauer & de Jong, 2006). The importance of phonological skills in determining visual-verbal PAL performance is also observed in typically developing readers. For example, individual differences in phonological skills predict visual-verbal PAL performance (de Jong et al., 2000; Windfuhr & Snowling, 2001). Furthermore, de Jong and colleagues (2000) showed that training in phonological awareness significantly improved visual-verbal PAL performance in kindergartners.

A phonological locus of PAL deficits can also account for the graded pattern of PAL deficits observed in dyslexia. When the verbal response to be learned is a nonword, PAL deficits are both robust and reliable, but when the response to be learned is a word, deficits are more equivocal (Elbro & Jensen, 2005; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003, 2006; Vellutino et al., 1975; Vellutino et al., 1978; Vellutino et al., 1983). Whether visual-verbal PAL deficits emerge for words seems to depend upon the nature of the verbal stimuli and the degree to which they tax the phonological system (e.g., de Jong et al., 2000; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003, 2006; Vellutino et al., 1995). For example, deficits are observed when stimuli comprise abstract or low frequency words, but are typically

absent for concrete words, or words that are high in frequency or imageability (Elbro & Jensen, 2005; Messbauer & de Jong, 2006; Samuels & Anderson, 1973; Vellutino et al., 1995). Such findings suggest that both the phonological demands of the stimuli (e.g. frequency, complexity) and the availability of non-phonological information (e.g. visual, semantic) influence the likelihood of observing PAL deficits in dyslexia. Viewed in this manner, the pattern of deficits observed in visual-verbal PAL seems a natural consequence of the degree to which learning hinges on phonological processes.

Clearly, the verbal component of visual-verbal PAL is crucial to explaining PAL deficits in dyslexia. However, evidence also suggests that visual-verbal PAL may index broader abilities than phonological processing alone. For example, Wimmer and colleagues (1998) reported PAL deficits in children with dyslexia even when they were matched to controls for phonological awareness. Additionally, visual-verbal PAL accounts for unique variance in reading ability in typically developing readers, above and beyond two of the best known cognitive predictors of reading ability: phonological awareness and rapid automatized naming (RAN) (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Thus, although it is tempting to conclude that deficits in visual-verbal PAL (in the absence of deficits in visual-visual PAL) arise as a consequence of verbal demands that are inherent in visual-verbal PAL, this conclusion is premature. Additional differences between these tasks must not be overlooked. One important difference is that visual-verbal PAL requires crossmodal (between-modality) mappings, whereas visual-visual PAL requires unimodal (within-modality) mappings. Because the contrast between these PAL mapping conditions confounds verbal and crossmodal demands, it does not allow for firm conclusions regarding the locus of PAL deficits in dyslexia.

Some researchers have argued that the crossmodal nature of visual-verbal PAL is central to its association with reading, as both require the establishment of visual-phonology mappings (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). According to their view, visual-verbal PAL taps a crossmodal mapping mechanism akin to that operating in connectionist models, in which learning occurs via the alteration of connection weights between orthographic and phonological units (Hulme et al., 2007; Seidenberg & McClelland, 1989; Snowling, 2000; Windfuhr & Snowling, 2001). Crucially, it is the learning of *associations* between visual and verbal stimuli, rather than the learning of the verbal stimuli itself, that is proposed to drive the relationship between visual-verbal PAL and reading. The primary evidence for the crossmodal hypothesis comes from a study by Hulme and colleagues (2007), in which the authors examined the specificity of the relationship between visual-verbal PAL and reading in typically developing children. The design included three mapping conditions: visual-verbal, visual-visual, and verbal-verbal. The verbal-verbal PAL task allowed Hulme et al. to evaluate whether crossmodal learning (e.g. visual-verbal), rather than unimodal verbal learning (e.g. visual-verbal, verbal-verbal) drives the relationship with reading ability. Although both visual-verbal and verbal-verbal PAL correlated significantly with reading skill, visual-verbal PAL was the only PAL task to predict unique variance in reading ability, consistent with there being a specific role for crossmodal mechanisms in reading.

However, the results of Chapter 2 are at odds with a crossmodal account of the PAL-reading relationship. By including four mapping conditions (visual-verbal, verbal-verbal, visual-visual, verbal-visual) the design introduced in Chapter 2 allowed for a strong test of the crossmodal hypothesis. If crossmodal associative learning is the crucial component of the task we would expect both visual-verbal and verbal-visual

PAL to show robust relationships with reading ability, as both require crossmodal mappings. However, the results were not in accordance with this hypothesis. Both visual-verbal and verbal-verbal PAL predicted unique variance in reading above and beyond phonological awareness and RAN, whereas verbal-visual and visual-visual PAL were unrelated to reading ability. The lack of a relationship between verbal-visual PAL and reading is difficult to reconcile with the crossmodal hypothesis, as this task, like visual-verbal PAL, has a crossmodal mapping demand. Instead, the results strongly suggest that verbal output demands are responsible for the PAL-reading relationship: both visual-verbal and verbal-verbal PAL explained variance in reading ability. Moreover, there was no evidence to support the view that visual-verbal PAL shares a unique relationship with reading ability. The shared variance between visual-verbal and verbal-verbal PAL fully accounted for the observed relationship with reading; visual-verbal PAL could not explain unique variance in reading ability above this shared “verbal output” component.

However, in Chapter 2 we reported data from typically-developing children and thus it remains possible that PAL deficits in dyslexia result from deficient crossmodal associative learning. Very few studies have addressed this issue, however. Vellutino and colleagues (1975) tested children with dyslexia in both visual-verbal PAL and visual-auditory PAL, a task in which associations are made between visual symbols and oral sounds (e.g., humming, coughing, puckering lips). Although both tasks required crossmodal associations (and oral production), deficits only emerged in visual-verbal PAL. Additionally, Torgesen and Murphey (1979) showed that these results held even when the oral output required was more complex, comprising a sequence of sounds. This is perhaps not surprising given that visual-auditory PAL does not tap the phonological system. However, while these findings clearly rule out a global deficit in

between-modality associative learning, they remain difficult to interpret. Although it is clear that the linguistic component of the task is imperative, it is not clear whether it is the verbal component alone, or the specific demand on visual-verbal associative learning that is responsible for the observed deficits.

We present three experiments designed to evaluate the specificity and locus of PAL deficits in dyslexia. In Experiment 3.1 and 3.2 we sought to determine whether PAL deficits are a consequence of verbal or crossmodal task demands. To do so, we used the factorial design introduced in Chapter 2, which allowed us to dissociate crossmodal and verbal demands in driving poor PAL performance in dyslexia. Experiment 3.3 expanded on the findings of Experiments 3.1 and 3.2 by investigating the stage of learning in which PAL deficits arise. Specifically, we were interested in whether PAL deficits stem from difficulties in phonological form learning, or whether they emerge in the process of binding verbal information to a referent in memory. To determine the stage at which deficits arise in dyslexia, we separated the verbal learning and associative learning components of a visual-verbal PAL task.

### **Experiment 3.1**

The primary aim of this experiment was to dissociate between crossmodal and verbal demands in driving PAL deficits in dyslexia. To do so, we tested the following PAL mapping conditions: visual-verbal, verbal-verbal, visual-visual, and verbal-visual. We predicted that if PAL deficits reflect crossmodal associative learning, deficits should emerge in both visual-verbal and verbal-visual PAL. On the contrary, if PAL deficits are a consequence of verbal deficits, impaired performance should emerge in both visual-verbal and verbal-verbal PAL. As outlined above, underlying phonological

deficits are likely to lead to poor performance on any PAL task with significant verbal demands. Thus we might expect verbal-verbal PAL to be impaired as a consequence of underlying phonological deficits. However, these demands may not fully account for PAL deficits in dyslexia; crossmodal demands may pose an additional and specific constraint on PAL performance. In this case, we would expect impairments in visual-verbal, verbal-visual, and verbal-verbal PAL. Note that although such a finding would implicate both verbal and crossmodal demands in poor PAL performance, it would still provide support for deficient crossmodal learning in dyslexia.

## **Method**

### **Participants**

Children with dyslexia (aged 8-12 years) were recruited from the local Dyslexia Association on the basis of attendance at a weekly tuition scheme for children with dyslexia. Enrollment in the tuition scheme is dependent upon a literacy screening battery administered by the local Dyslexia Association. Thus, all children attending the tuition scheme have been previously identified as having significant literacy difficulties that warranted specialist teaching outside of school. Typically developing readers (aged 8-12 years) were recruited from two state primary schools serving socially-mixed catchment areas in Oxfordshire, UK. All participants spoke English as a first language. Upon obtaining consent, the children were screened via a battery of five standardized assessments of reading, two literacy-related measures, and a test of nonverbal reasoning. These allowed us to select children to participate in our experiment (see below for criteria):

*Nonverbal Reasoning.* The Wechsler Abbreviated Scale of Intelligence (WASI) Matrix Reasoning (WASI; Wechsler, 1999) subtest provided an estimate of cognitive

ability. The test consists of 35 abstract spatial reasoning problems in which an array is presented with one missing section. Participants must choose the item that belongs in the array from five options.

*Passage Reading Accuracy.* The York Assessment of Reading for Comprehension (YARC; Snowling et al., 2009) provided a measure of passage reading accuracy. In this test, children are instructed to read short passages aloud as quickly and accurately as possible.

*Passage Reading Rate.* The reading rate subscale of the YARC provided a measure of reading fluency. Standardized scores are computed based on the total time (in seconds) taken to read each passage.

*Single Word Reading.* The Single Word Reading Test (SWRT; Foster, 2007) was administered as a measure of untimed single word reading ability.

*Word Reading Fluency.* The Sight Word Efficiency subtest from the Test of Word Reading Efficiency (TOWRE; Torgesen et al., 1999) measured word reading fluency. The raw score is defined as the total number of words (out of 104) that can be read correctly in 45 seconds.

*Nonword Reading Fluency.* The Phonemic Decoding Efficiency subtest from the TOWRE (Torgesen et al., 1999) measured nonword reading fluency. The raw score is the total number of nonwords read correctly in 45 seconds.

*Phoneme Deletion.* The Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999) assessed phonological awareness (PA). In this test children are asked to delete single phonemes from words (e.g., “Say *bold* without the *b*”).

*Rapid Automatized Naming.* In rapid digit naming subtest of the CTOPP, six digits (e.g., 4, 7, 8, 5, 2, 3) are repeated six times throughout a 36-item matrix arranged

in four rows of nine items. Children must name the items in the matrix sequentially, starting at the top of the page from left to right as quickly as possible until they have named all 36 items. Children complete two separate arrays that differ only in the order the digits are presented. The time (in seconds) taken to name the items in each array is summed to produce a total naming time.

#### *Group Selection*

Participants were included in the dyslexia group if they (a) had a formal diagnosis of dyslexia and (b) obtained standard scores one standard deviation or below the mean on three or more of the five measures of reading. This yielded a final group of 18 children with dyslexia (9 boys, 9 girls). A control group of 18 typically developing readers (11 boys, 7 girls) was next selected and matched to the dyslexic group for chronological age and nonverbal reasoning. All children in this group scored within the average range on five or more of the seven literacy measures. The descriptive characteristics of the groups are displayed in Table 3.1. As expected, the children with dyslexia performed more than one standard deviation below the mean across measures of reading and reading-related skill. In contrast, the typically developing readers performed within the normal range.

Table 3.1

*Descriptive characteristics of dyslexic and control groups*

Measures	Dyslexic		Control	
	M	SD	M	SD
Age (years)	10.14	1.07	10.01	0.87
WASI Matrices <sup>a</sup>	53.22	5.20	51.51	6.11
<i>Selection Measures</i>				
Sight Word Efficiency <sup>b</sup>	82.72	11.71	105.44	7.67
Phonemic Decoding Efficiency <sup>b</sup>	79.33	8.33	108.61	8.90
Single Word Reading <sup>b</sup>	76.61	6.35	105.11	10.32
Passage Reading Accuracy <sup>b</sup>	77.06	4.92	103.72	7.31
Passage Reading Rate <sup>b</sup>	78.59	8.60	110.39	10.31
<i>Reading-related Skills</i>				
Phoneme Deletion <sup>c</sup>	6.89	1.84	11.06	2.49
RAN Digits <sup>c</sup>	6.78	1.80	10.00	2.35

*Notes.* <sup>a</sup>T score,  $M = 50$ ,  $SD = 10$ , <sup>b</sup>standard score,  $M = 100$ ,  $SD = 15$ , <sup>c</sup>scaled score,  $M = 10$ ,  $SD = 3$

## Design

The design was within-participant with all children completing all four PAL mapping conditions: visual-verbal, verbal-verbal, visual-visual, and verbal-visual. Children were tested in four sessions across a four-week period. Only one condition was tested per week to minimize interference between conditions and the order in which children completed the conditions was counterbalanced.

## Materials and Procedure

Children learned six stimulus-response pairs per mapping. The stimulus-response pairs were fixed, such that all participants learned the same pairings for each condition. Within each of the four conditions, the presentation of the stimulus-response pairs was randomized in every trial. For stimulus-response pairs across the experiments reported in this chapter, refer to Appendix A.

*Visual Stimuli.* The abstract symbols were chosen from extinct written languages (e.g., Akkadian). Fifteen adults rated 54 potential stimulus items on a scale of 1-10 (with 10 being most difficult) for degree of verbalization (i.e., “how easy is it to assign a verbal label or description to this item?”), and ease of drawing (i.e., “how easy is it to draw this item?”). The 24 symbols rated the hardest to verbalize were assigned to four sets (i.e., two sets of stimulus items, and two sets of response items) that comprised the visual stimuli for the PAL conditions. The visual stimuli were matched for degree of verbalization across the four sets,  $F(3, 42) = 2.11, p = .114$ . Additionally, we ensured that the two sets comprising visual response items were matched for ease of drawing,  $F(1, 14) = 1.26, p = .280$ .

*Verbal Stimuli.* The verbal stimuli comprised phonotactically legal CVC nonwords, chosen from the ARC Nonword Database (Rastle et al., 2002). Each of the short vowel sounds (i.e., a, e, i, o, u) and one long vowel sound (e.g., ee) were used

once per stimulus set. Additionally, no two items shared consonant positioning (i.e., first or last sound) within a stimulus set, in an effort to minimize phonological similarity between items.

*Paired Associate Learning.* Children were tested individually in a quiet room in their school. The experiment was run using EPrime Version 2.0 (Schneider et al., 2007) presented on a Dell laptop. In each condition, the six stimulus-response pairs were presented in two presentation blocks before the test trials began. In the first presentation block, children were instructed to repeat the response item after each presentation to ensure that the responses could be accurately reproduced. For verbal response items, children were instructed to repeat each nonword aloud; for visual response items, children were instructed to draw the abstract symbol inside a booklet of blank index cards, one item per page to prevent them from referring to previous responses throughout a block. If a nonword or symbol was reproduced incorrectly the experimenter corrected the child by saying “that’s not quite right,” and then proceeded to repeat the correct nonword or draw the correct response in the booklet for the child. In the second presentation block the children were asked to focus on learning the pairs of items rather than reproduce the response item. This followed from pilot testing in which instructing participants to focus on the stimulus-response pairings resulted in better learning than instructing them to reproduce the response items in the second presentation block.

Five blocks of learning trials followed the presentation blocks. Each block consisted of six trials, one for each stimulus-response pair. In each trial, the stimulus item was presented on the computer and the participant was then asked to provide the appropriate response (e.g., “What goes with hib?”). Depending on the output required, the child either drew the symbol in the booklet or verbally produced the nonword that

corresponded to the stimulus item. This procedure required production for all conditions regardless of modality, thus avoiding a common confound in the literature in which recall is required for verbal stimuli and recognition for visual stimuli (Messbauer & de Jong, 2003). Regardless of the accuracy of the child's response, the correct answer was presented on the computer immediately following each trial. This procedure was repeated for each trial across all five blocks. All participants completed all trials, and accuracy per trial and total learning across trials was recorded. The final score was calculated as the total number of correct trials across all five blocks (maximum score of 30). The reliability of PAL tasks will be addressed in detail in Chapters 4 and 5. Cronbach's alpha for the PAL tasks administered in the experiments reported in this chapter can be found in Table 5.1 (Chapter 5).

### **Results**

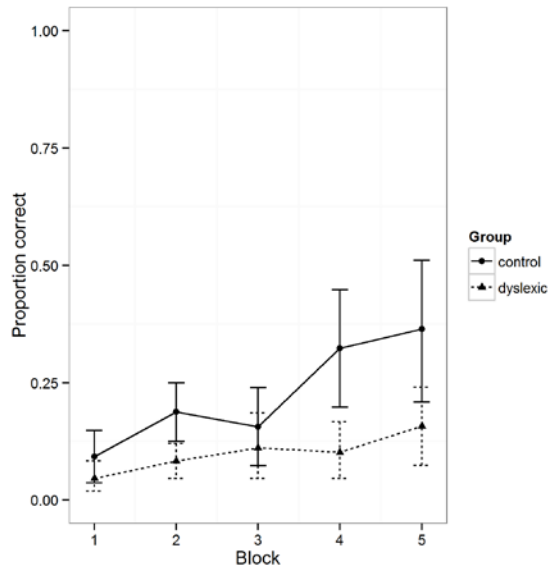
The mean scores and standard deviations across the four PAL mapping conditions for both reader groups are shown in Table 3.2. Learning across blocks by group and mapping condition is displayed in Figure 3.1.

Table 3.2

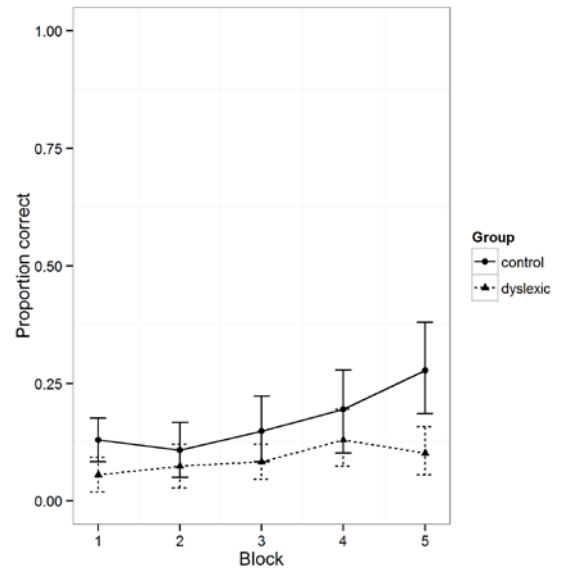
*Mean (SD) performance on PAL tasks in Experiment 3.1*

	Dyslexic		Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Visual-Verbal PAL (max 30)	3.00	2.97	6.72	4.50
Verbal-Verbal PAL (max 30)	2.67	2.25	5.11	3.92
Visual-Visual PAL (max 30)	10.28	5.63	10.06	5.40
Verbal-Visual PAL (max 30)	11.39	5.18	12.61	4.51

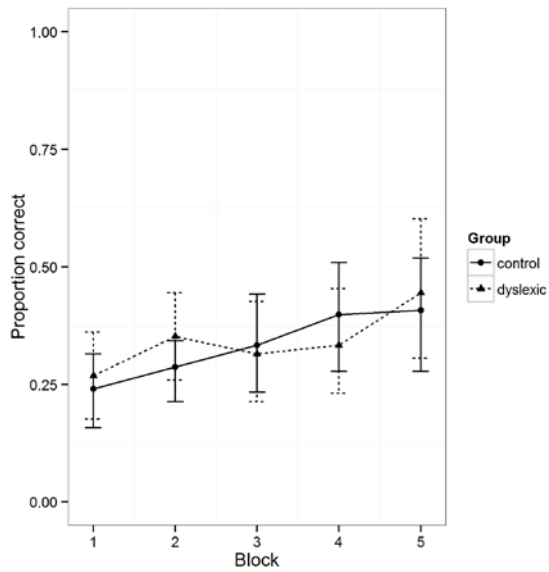
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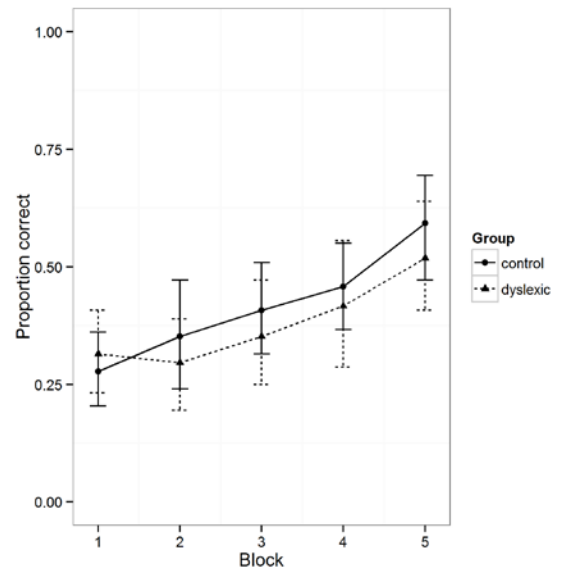
B



C



D



*Figure 3.1.* Proportion correct across learning blocks for the dyslexic and control group in Experiment 3.1: (A) visual-verbal PAL, (B) verbal-verbal PAL, (C) visual-visual PAL, or (D) verbal-visual PAL. Error bars represent 95% confidence intervals.

Upon initial observation it is clear that overall performance varied by mapping condition, with both groups of children finding verbal output conditions (visual-verbal, verbal-verbal) more difficult than the visual output conditions (visual-visual, verbal-visual). This observation is in line with the pattern of performance reported by Hulme et al. (2007) in children of this age, and our own results reported in Chapter 2. Despite this general trend in performance, however, it is apparent that the dyslexic group performed less well than the control group in visual-verbal and verbal-verbal PAL. This pattern immediately suggests that PAL deficits stem from verbal, rather than crossmodal or general associative learning difficulties, as performance is comparable to the control group in verbal-visual and visual-visual PAL. To examine the effects of PAL modality and output on group performance, the results were analysed in a logistic linear mixed-effects model implemented in the lme4 package in R (Bates, Maechler, & Bolker, 2011). This analysis was chosen over traditional ANOVA for two reasons. First, such models allow for crossed random effects, such that variability can be accounted for across both participants and items simultaneously (Baayen, Davidson, & Bates, 2008). Second, ANOVA can lead to spurious results when the dependent variable constitutes a binary outcome, even when classic transformations have been applied (Jaeger, 2008).

In all mixed-effects analyses reported below we utilized a maximal random effects structure, (i.e. by-subject and by-item slopes for each fixed main effect and interaction). Failing to include random slopes in models with substantial by-participants or by-items differences can lead to inaccurate inferences and impose limitations on the generalization of the fixed effects (see Barr, Levy, Scheepers, & Tily, 2012; Roland, 2009). Additionally, we centered all fixed effects around their mean, thus minimizing collinearity and aiding in model interpretation. Finally, as suggested by Baayen et al.

(2008), *p*-values for mixed logistic regression models were calculated based on the Wald *Z* statistic.

The effect of PAL mapping modality and output demand on experimental group was tested in a model with modality (crossmodal, unimodal), output (verbal, visual), group (dyslexic, control), and block (1-5) as fixed effects, and participant and item as random effects. Fixed effects are shown in Appendix B. Results revealed main effects of output (OR = 4.91, 95 % CI [3.25, 7.42],  $Z = 7.56$ ,  $p < .001$ ), group, (OR = 0.62, 95 % CI [0.40, 0.96],  $Z = -2.14$ ,  $p = .03$ ), and block (OR = 1.30, 95 % CI [1.20, 1.40],  $Z = 6.32$ ,  $p < .001$ ), but no main effect of modality (OR = 0.79, 95 % CI [0.51, 1.22],  $Z = -1.07$ ,  $p = .283$ ). The main effect of block indicates that learning occurred across tasks and groups; however, there were no significant interactions with any of the fixed effects. In contrast to the predictions of the crossmodal hypothesis, the interaction of group and modality was not significant, (OR = 1.28, 95 % CI [0.67, 2.44],  $Z = 0.75$ ,  $p = .453$ ). Instead, there was a significant interaction between output and group, (OR = 2.28, 95 % CI [1.29, 4.04],  $Z = 2.83$ ,  $p = .005$ ). Tests of simple main effects revealed that children with dyslexia performed significantly poorer than chronological age controls in verbal output conditions, (OR = 0.49, 95 % CI [0.26, 0.93],  $Z = -2.20$ ,  $p = .028$ ) but equally well in visual output conditions, (OR = 1.00, 95 % CI [0.69, 1.46],  $Z = -0.00$ ,  $p = .998$ ).

### Discussion

Experiment 3.1 examined whether the locus of PAL deficits in children with dyslexia reside at the level of modality or output. Consistent with the literature, children with dyslexia were poor at visual-verbal PAL, but performed as well as age-matched controls in the visual-visual condition, a nonverbal test of PAL (Messbauer & de Jong, 2003; Steger, Vellutino, & Meshoulam, 1972; Vellutino et al., 1975).

However, the addition of the verbal-verbal and verbal-visual conditions to our design made it possible to dissociate between a verbal and crossmodal explanation of visual-verbal PAL deficits. Children with dyslexia were selectively impaired in visual-verbal and verbal-verbal PAL, but not visual-visual or verbal-visual PAL. Together, these findings provide clear support for a verbal explanation of PAL deficits in children with dyslexia. Most importantly, the factorial design allowed for the dissociation of modality and output, thus providing direct evidence against a theory of deficient crossmodal mapping mechanisms in dyslexia.

Although the data speak clearly to our experimental question, it is evident that the children found the tasks difficult. In particular, low performance levels in visual-verbal and verbal-verbal PAL indicate that the tasks may be limited in their sensitivity to capture the full range of abilities. Floor effects are of particular concern in the dyslexic group, in which there is little evidence of learning across trials. Although floor effects may influence the accuracy of the estimate of the population mean and effect size, it is important to note that reliable differences between the dyslexic and control groups still emerged. Thus, despite the difficulty of the task, the control group still learned significantly more than the dyslexic group in visual-verbal and verbal-verbal PAL. Perhaps more germane to our argument is the fact that differences did not emerge in verbal-visual PAL, a task in which performance levels signal little concern. If children with dyslexia are specifically impaired in forming crossmodal associations, we would expect performance differences in this condition. Instead, the results clearly show that children with dyslexia struggle only in PAL tasks with a verbal output component.

## Experiment 3.2

The results of Experiment 3.1 favor a verbal account of PAL deficits in dyslexia. However, the extent of these deficits and their relation to learning over time is difficult to discern due to low performance levels. Experiment 3.2 was designed to capture a wider range of performance by increasing performance levels across PAL conditions. To do so, we decreased the number of items per mapping condition from six to four in visual-verbal and verbal-verbal PAL and from six to five in visual-visual and verbal-visual PAL (note we used a different number of items per condition to better equate performance across the four conditions). An additional aim of Experiment 3.2 was to assess the nature of the errors made by the children, and to ask whether the errors made by children with dyslexia differ from those made by typically developing children. We hypothesized that if PAL deficits are driven by verbal demands, as Experiment 3.1 suggests, the errors made by children with dyslexia should be phonological in nature (i.e., phonologically distorted word, correct pairing). If however, PAL deficits are caused by a specific difficulty with associative learning, we would expect a higher proportion of associative learning errors (i.e., correct word form, incorrect pairing). To examine this question, we tracked the errors made by participants in visual-verbal and verbal-verbal PAL. Finally, given the frequent co-occurrence of dyslexia and specific language impairment (SLI), it is possible that children with dyslexia perform worse than controls due to concomitant oral language deficits. To evaluate this possibility, we measured expressive vocabulary in both groups. Additionally, we measured digit span as a proxy of verbal short term memory, as group differences in this factor could potentially limit learning of the phonological forms in visual-verbal and verbal-verbal PAL.

## Method

### Participants

Children with dyslexia were recruited from three private schools for children with specific learning difficulties in Boulder, Denver, and Littleton, Colorado. Informed consent forms were only sent home with children who were officially identified by the school as having a specific reading disability in the absence of diagnosed attentional or behavioral difficulties. Typically developing readers aged 8-13 were recruited from a private primary school in Boulder, Colorado and a public primary school in Centennial, CO. All participants came from a middle class or upper-middle class background and spoke English as a first language.

Informed consent was obtained for 20 children with a documented history of dyslexia, and 23 typically developing readers. Upon obtaining consent, the children were assessed with a cognitive battery consisting of the following reading and reading-related measures: Word Reading Fluency (TOWRE), Nonword Reading Fluency (TOWRE), Phoneme Deletion (CTOPP), Rapid Automated Naming (CTOPP), and Digit Span (CTOPP). In addition to these measures, children were given assessments of nonverbal reasoning (WASI), and Expressive Vocabulary (from the Clinical Evaluation of Language Fundamentals, CELF-4). Given the extensive documented history of the children with dyslexia, the test battery was utilized as a confirmatory measure; that is, children remained in the sample unless they scored above the 25th percentile on three or more of the reading-related measures. This resulted in a final sample of 18 children with dyslexia (13 boys, 5 girls). We next selected a control group of 18 typically developing readers (12 boys, 6 girls), matched to the dyslexic group on age and nonverbal reasoning. All children in this group had no documented history of special educational needs, and scored above the 25th percentile on three or more of the literacy

measures. Descriptive characteristics of the groups are shown in Table 3.3. The dyslexic group scored significantly below the controls on all reading and reading-related measures, except expressive vocabulary,  $t(34) = 1.53$ ,  $p = .137$ . Additionally, it should be noted that although the groups differed in digit span, performance in the dyslexic group was well within the normal range.

Table 3.3

*Descriptive characteristics of dyslexic and control groups in Experiment 3.2*

Measures	Dyslexic		Control	
	M	SD	M	SD
Age (years)	11.13	1.34	10.57	1.00
WASI Matrices <sup>a</sup>	51.12	7.04	52.28	8.60
Expressive Vocabulary <sup>b</sup>	40.39	6.52	44.67	9.96
Sight Word Efficiency <sup>c</sup>	81.75	8.58	110.00	13.18
Phonemic Decoding Efficiency <sup>c</sup>	84.19	5.79	107.44	12.43
Phoneme Deletion <sup>d</sup>	7.56	2.07	11.00	2.30
RAN Digits <sup>d</sup>	5.94	1.39	10.71	2.14
Digit Span <sup>d</sup>	9.28	0.66	11.78	0.76

*Notes.* <sup>a</sup>T score,  $M = 50$ ,  $SD = 10$ , <sup>b</sup>raw score (max. 54), <sup>c</sup>standard score,  $M = 100$ ,  $SD = 15$ , <sup>d</sup>scaled score,  $M = 10$ ,  $SD = 3$

## Materials and Procedure

The design was identical to that of Experiment 3.1, except where noted below. All participants completed the four PAL mapping conditions, with one condition tested per week. The stimuli were the same as those utilized in Experiment 3.1. However, the number of stimulus-response pairs in each condition was reduced. Participants learned four stimulus-response pairs across five blocks for visual-verbal and verbal-verbal PAL (maximum score of 20 per condition), and five stimulus-response pairs across five blocks for visual-visual and verbal-visual PAL (maximum score of 25 per condition). The procedure was identical to that of Experiment 3.1 with the addition of each verbal response being transcribed, allowing a detailed error analysis to be made.

## Results

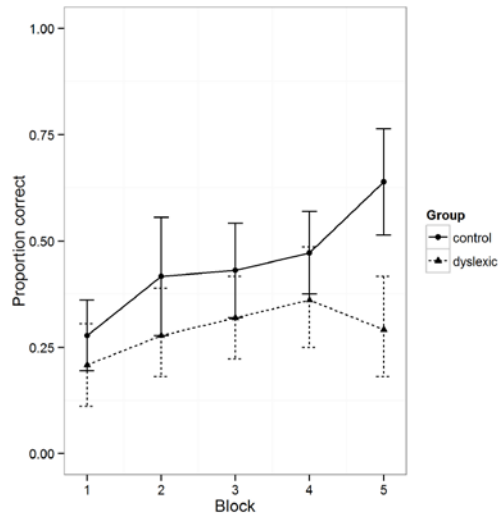
The mean scores and standard deviations across the four PAL mapping conditions for both reader groups are shown in Table 3.4. Learning across blocks by group and mapping condition is displayed in Figure 3.2.

Table 3.4

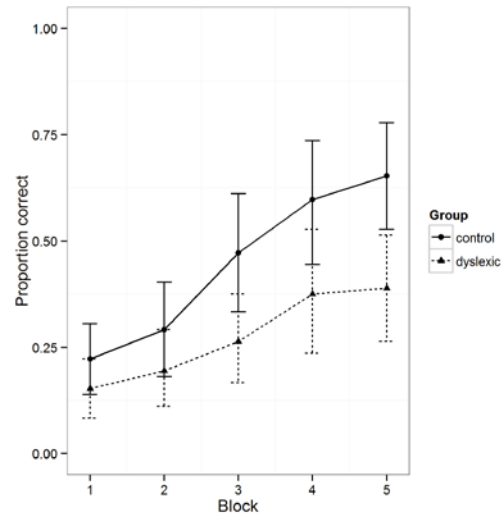
*Mean (SD) performance across PAL tasks in Experiment 3.2*

	Dyslexic		Control	
	M	SD	M	SD
Visual-Verbal PAL (max. 20)	5.83	3.87	9.39	3.88
Verbal-Verbal PAL (max. 20)	5.50	3.79	9.50	4.33
Visual-Visual PAL (max. 25)	13.33	4.83	13.39	4.27
Verbal-Visual PAL (max .25)	14.06	4.95	14.89	3.66

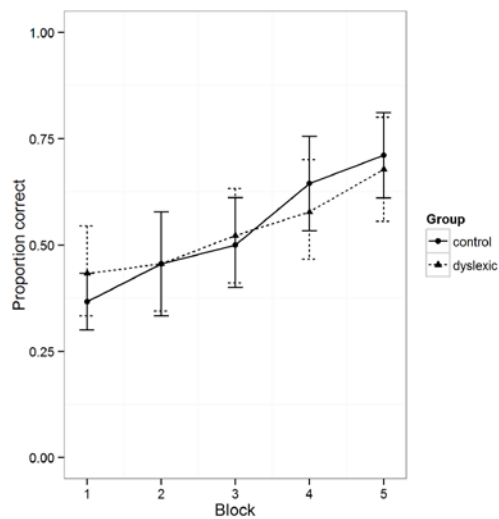
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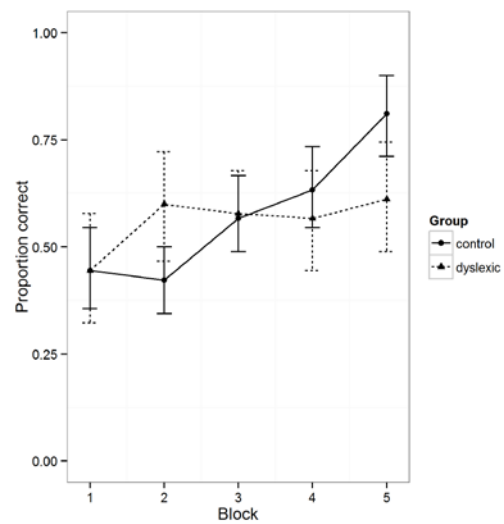
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D



*Figure 3.2.* Proportion correct across learning blocks for the dyslexic and control group in Experiment 3.2: (A) visual-verbal PAL, (B) verbal-verbal PAL, (C) visual-visual PAL, or (D) verbal-visual PAL. Error bars represent 95% confidence intervals.

As in Experiment 3.1, the data were analysed with logistic linear mixed-effect modelling with maximal random effects structure. The effects of mapping modality and output demand on PAL performance was tested in a model with modality (crossmodal, unimodal), output (verbal, visual), group (dyslexic, control), and block (1-5) as fixed effects, and participant and item as random effects. Fixed effects are displayed in Appendix B. Results revealed significant main effects of output (OR = 2.60, 95 % CI [1.48, 4.57],  $Z = 3.33$ ,  $p < .001$ ) and block (OR = 1.44, 95 % CI [1.32, 1.57],  $Z = 8.30$ ,  $p < .001$ ), but no main effect of group (OR = 0.68, 95 % CI [0.43, 1.09],  $Z = -1.59$ ,  $p = .113$ ) or modality (OR = 0.88; 95 % CI [0.52, 1.50],  $Z = -0.48$ ,  $p = .635$ ). A significant interaction between block and group (OR = 0.79, 95 % CI [0.69, 0.90],  $Z = -3.59$ ;  $p < .001$ ) was qualified by follow-up tests indicating the groups only differed on blocks 4 (OR = 0.57, 95 % CI [0.35, 0.92],  $Z = 2.46$ ,  $p = .014$ ) and 5 (OR = 0.36, 95 % CI [0.19, 0.69],  $Z = 4.06$ ,  $p < .001$ ). Replicating the key findings of Experiment 3.1, the interaction between output and group was significant (OR = 2.27, 95 % CI [0.85, 1.21],  $Z = 2.76$ ,  $p = .006$ ), whereas there was no interaction between modality and group (OR = 1.01; 95 % CI [0.63, 1.62];  $Z = 0.06$ ,  $p = .954$ ). Tests of simple main effects revealed that the interaction between group and output was driven by a significant group difference in performance for verbal output (OR = 0.32, 95 % CI [0.19, 0.54],  $Z = -4.20$ ,  $p < .001$ ), but not visual output PAL conditions (OR = 0.96, 95 % CI [0.54, 1.69],  $p = .877$ ).

#### *Analysis of Errors*

The errors made in the two verbal output conditions were scored and categorized by the type of error made. Given the lack of group differences in the two visual output conditions in the overall analyses, further investigation of those errors was unnecessary. We first removed “don't know” responses from the total errors so that all proportions

reflected errors in which a child attempted a response. Errors were categorized into three main categories: association errors (i.e. correctly pronounced nonword, incorrect pairing), phonological errors (i.e. incorrectly pronounced nonword), and intrusion errors (i.e. responding with an item from a previously learned condition). Because phonological errors represented a wide range of phonological distortions, these errors were further investigated by separating errors according to the extent to which they deviated from the target. Responses were classified as single feature errors if they deviated by only one phoneme (e.g. “vep” for “vek”), and multiple feature errors if they deviated by two or more phonemes (e.g. “zep” for “vek”). The majority of errors (88%) respected syllable structure (CVC) and errors occurred at all positions within that structure. A final question of interest was whether children with dyslexia repeated errors more frequently than age-matched controls. These “perseveration errors” were calculated as the proportion of pronunciation errors that were repeated across multiple trials. The error data for each group (by condition) is presented in Table 3.5. For all tests reported below, differences in the patterns of proportions between groups were tested in log-linear mixed effects models in the lme4 package in R. In each model, the proportion of errors was predicted by a random effect of subject, and fixed effects for error type, group, and the interaction between the two. An observation-level random effect was also included to account for overdispersion (indicated by higher observed variance than would be expected from the theoretical binomial distribution) (e.g., Maindonald & Braun, 2010; Rigby, Stasinopoulos, & Akantziliotou, 2008).

Table 3.5

*Proportion errors by type and group in visual-verbal PAL and verbal-verbal PAL in Experiment 3.2*

	Dyslexic		Control	
	M	SD	M	SD
<i>Visual-Verbal PAL</i>				
Intrusion	.02	.01	.06	.03
Association	.32	.05	.34	.05
Phonological	.66	.06	.60	.05
Single Feature	.57	.08	.68	.07
Multiple Feature	.43	.08	.32	.07
Perseverations	.48	.08	.45	.08
<i>Verbal-Verbal PAL</i>				
Intrusion	.05	.02	.08	.04
Association	.21	.05	.32	.05
Phonological	.74	.05	.60	.07
Single Feature	.33	.06	.54	.07
Multiple Feature	.67	.06	.46	.07
Perseverations	.29	.06	.30	.07

*Visual-Verbal PAL*

"Don't know" responses accounted for 8% of errors made by children with dyslexia, and 7% made by the controls. After removing these, it is clear that the pattern of errors is similar for both groups, with phonological errors comprising the majority of errors, followed by association errors, and finally, intrusion errors, which were relatively rare. Results of a log-linear mixed effects model revealed a main effect of error type (OR = 2.36, 95 % CI [1.56, 3.58],  $Z = 4.05$ ,  $p < .001$ ), but no main effect of group (OR = 0.91, 95 % CI [0.45, 1.84],  $Z = -0.27$ ,  $p = .788$ ), and no interaction between group and error type (OR = 1.36, 95 % CI [0.59, 3.13],  $Z = 0.73$ ,  $p = .466$ ). These results indicate that although the dyslexic group made more errors than the control group overall, the pattern and relative proportions of errors were similar across groups.

Although the overall pattern of proportions did not differ, we were interested in the extent to which phonological errors deviated from the target word. Errors that share more phonemic features with the target word may be viewed as less severe phonological distortions than those sharing fewer features in common. To examine this possibility we tested for group differences in single versus multiple feature phonological errors. Because single and multiple feature errors are mutually dependent (i.e. knowing the proportion of one category defines the proportion of the other category), group differences were only tested for multiple feature errors. Note that had we tested differences in single feature errors the resulting models would be identical. Although the dyslexic group appeared to commit a higher proportion of multiple feature errors than controls, this difference was not statistically significant (OR = 2.00, 95 % CI [0.72, 5.56],  $Z = 1.34$ ,  $p = .181$ ). Finally, there was no indication that the groups differed in

how often they repeated the same errors (i.e. perseveration errors) (OR = 0.97, 95 % CI [0.36, 2.61],  $Z = -0.06$ ,  $p = .953$ ).

#### *Verbal-Verbal PAL*

“Don't know” responses constituted 9% and 12% of errors made by the dyslexic and control groups respectively. After removing these, the pattern of errors closely resembled that of visual-verbal PAL, with the majority of errors being phonological in nature. Results of a log-linear mixed effects model revealed a main effect of error type (OR = 7.05, 95 % CI [4.83, 10.28],  $Z = 10.13$ ,  $p < .001$ ), but no main effect of group (OR = 0.78, 95 % CI [0.43, 1.40],  $Z = -0.84$ ,  $p = .404$ ). A significant interaction between group and error type (OR = 2.99, 95 % CI [1.40, 6.37],  $Z = 5.77$ ,  $p < .001$ ) revealed that whereas the proportions of errors did not differ between groups for intrusion errors (OR = 0.53, 95 % CI [0.16, 1.78],  $Z = -1.03$ ,  $p = .303$ ), they differed significantly for association errors (OR = 0.33, 95 % CI [0.13, 0.81],  $Z = -2.41$ ,  $p = .016$ ), and to an even greater extent for phonological errors (OR = 3.50, 95 % CI [1.43, 8.53],  $Z = 2.75$ ,  $p = .006$ ).

These results were followed up with a closer examination of the nature of the phonological errors, as described for visual-verbal PAL. A log-linear mixed effects model revealed that the dyslexic group committed a higher proportion of multiple feature errors than the control group (OR = 2.97, 95 % CI [1.39, 6.32],  $Z = 2.82$ ,  $p = .005$ ). As in visual-verbal PAL, however, there was no difference in the proportion of perseveration errors made by each group (OR = 0.78, 95 % CI [0.25, 2.47],  $Z = -0.42$ ,  $p = .677$ ).

## Discussion

The results of Experiment 3.2 align closely with those of Experiment 3.1, replicating the finding of deficits specific to verbal output conditions (i.e. visual-verbal, verbal-verbal PAL) in children with dyslexia. Together, the results of these experiments implicate verbal deficits in driving poor PAL performance in dyslexia. Moreover, there was no evidence for global crossmodal associative learning deficits (i.e. both visual-verbal and verbal-visual PAL), nor were the observed PAL deficits restricted to crossmodal conditions.

Further support for the view that PAL deficits are a consequence of underlying deficits in the verbal domain comes from the error analyses. Despite making more errors in visual-verbal and verbal-verbal PAL overall, children with dyslexia did not commit a higher proportion of associative errors, suggesting that poor PAL performance does not result from difficulties with the associative demands of the task. Instead, the errors were indicative of phonological learning deficits. Children with dyslexia made a similar proportion of phonological errors as controls in visual-verbal PAL, and a greater proportion of phonological errors in verbal-verbal PAL. The higher proportion of errors in verbal-verbal PAL may have resulted from the increased phonological demands of the task (both verbal input and output demands) in comparison to visual-verbal PAL (only verbal output demands). However, in both conditions, children with dyslexia tended to produce errors that were phonologically further from the target than controls. Together, these findings clearly indicate that PAL deficits in dyslexia are specific to those conditions that require a verbal output.

### Experiment 3.3

The findings of Experiment 3.1 and Experiment 3.2 provide strong evidence that PAL deficits in dyslexia stem from the verbal demands of the task, rather than difficulties in crossmodal associative learning. However, despite demonstrating the specificity of deficits to verbal output conditions, they cannot speak to the locus of these difficulties. Do they arise during the verbal learning or associative stage of PAL? Evidence supports the notion that the phonological and associative components of PAL tasks are indeed dissociable (Duyck, Szmalec, Kemps, & Vandierendonck, 2003; Freedman & Martin, 2001). Importantly, difficulties at either (or both) stages of learning would lead to the verbal-output PAL deficits observed in Experiment 3.1 and 3.2. Traditional nonword PAL paradigms are confounded by the fact that verbal learning and associative learning occur simultaneously, making it difficult to estimate the effects of verbal learning and associative learning on performance. Yet, locating the source of failure is crucial for guiding our conceptualization of PAL deficits in dyslexia. If deficits arise solely from demands on verbal learning, PAL deficits should be viewed as a corollary of verbal deficits, rather than a defining feature of dyslexia. If, however deficits emerge in the associative learning phase, a different explanation might be necessary, giving special status to difficulties associating verbal output with other stimuli.

Experiment 3.3 was designed to address these confounds by separating the learning procedure into a verbal learning and associative learning phase. This was achieved by presenting the children with verbal stimuli in a pre-exposure phase, before requiring them to associate the verbal forms with input stimuli. The primary question of interest was whether verbal learning ability, as indexed by the pre-exposure phase,

would fully account for any observed difference between dyslexic and control groups in a test of visual-verbal PAL. We hypothesized that differences in verbal learning in the pre-exposure phase would fully explain deficits in visual-verbal PAL in the associative learning phase. That is, we expected no difference between the dyslexic and control groups in visual-verbal PAL, *after* accounting for verbal learning ability. If, however, children with dyslexia have an additional difficulty binding verbal information to a referent in memory, we would expect PAL deficits to be additive, such that they are more severe than would be predicted solely from underlying language deficits.

### **Participants**

Dyslexic children were selected from a specialist state school in the UK for children with specific learning difficulties. This school provides provision to children with longstanding reading difficulties that have proved resilient to intervention provided by their local school. All children undergo a comprehensive educational assessment before entry into the school. Together with teacher reports, these assessments were used to select a group of children with dyslexia, with whom informed consent forms were sent home. Control children were selected from two state schools in London, UK serving middle and upper-class catchment areas. Informed consent forms were sent home with all children in Grades 4 and 5 (ages 9-11).

Upon obtaining consent, the children were assessed with a cognitive battery consisting of the following literacy measures: Word Reading Fluency (TOWRE), Nonword Reading Fluency (TOWRE), Phoneme Deletion (CTOPP), Digit Span (CTOPP), Rapid Automated Naming (CTOPP), and Single Word Reading from the Wechsler Objective Reading Dimensions test (WORD) (Wechsler, 1993). These measures came from a battery administered as part of a larger study. Due to the

constraints of the larger study, it was unfortunately not possible to administer a test of expressive vocabulary.

Given the extensive history of the children with dyslexia, the test battery was utilized as a confirmatory measure; that is, children remained in the sample unless they scored above the 25th percentile on three or more of the reading and reading-related measures. This criterion resulted in a final sample of 14 children with dyslexia (8 boys, 6 girls). A control group of 14 typically developing readers (6 boys, 8 girls), matched to the dyslexic group on age and nonverbal reasoning was next selected. All children in this group had no documented history of special educational needs, and scored above the 25th percentile on all literacy measures. All participants spoke English as a first language.

The descriptive characteristics of the groups are displayed in Table 3.6. As expected, the children with dyslexia performed far below the level of controls across literacy measures, despite being matched with the controls on age and nonverbal reasoning.

Table 3.6

*Descriptive characteristics of dyslexic and control readers in Experiment 3.3*

Measures	Dyslexic		Control	
	M	SD	M	SD
Age (years)	10.61	0.62	10.30	0.30
WASI Matrices <sup>a</sup>	52.50	5.08	56.21	7.61
Sight Word Efficiency <sup>b</sup>	86.71	7.53	115.36	8.38
Phonemic Decoding Efficiency <sup>b</sup>	82.64	8.13	117.93	15.01
Single Word Reading <sup>b</sup>	81.50	7.02	113.36	9.16
Phoneme Deletion <sup>c</sup>	8.00	2.60	11.64	2.90
RAN Digits <sup>c</sup>	8.21	2.22	11.64	3.25
Digit Span <sup>c</sup>	6.89	.77	12.21	.85

*Notes.* <sup>a</sup>T score,  $M = 50$ ,  $SD = 10$ , <sup>b</sup>standard score,  $M = 100$ ,  $SD = 15$ , <sup>c</sup>scaled score,  $M = 10$ ,  $SD = 3$

### **Materials and Procedure**

Children were tested in two sessions on consecutive days. On day one children completed the verbal pre-exposure stage in which they were familiarized with and asked to learn the verbal response items. On day two children learned the visual-verbal paired associates. The verbal stimuli used for the paired associates were the same as those used in the verbal pre-exposure stage. The experiment was presented on a Dell laptop using EPrime Version 2.0.

*Verbal Pre-Exposure.* The verbal stimuli were five CVC nonwords chosen at random from the stimuli used in Experiment 3.1. The children watched a short introductory animation in which aliens crashed to earth and needed help returning to their planet. The children were told that they needed to learn some words from the

“alien” language. The experiment began with a block of immediate repetition trials in which each of the five nonwords was presented in random order. Children were asked to repeat each nonword aloud immediately after hearing it. This initial block served as a check for the children’s ability to hear and orally reproduce the nonwords. If a child mispronounced a word, the experimenter responded by saying, “That’s not quite right. The word is ‘X’ ”. This was followed by a serial recall game with three blocks of increasing difficulty. This game served to familiarize the children with the nonwords. In the first block, two nonwords were presented sequentially, and the children were asked to repeat them back in the same order. In the next block, children heard the remaining three nonwords and were asked to repeat them back in the same order in which they were presented. In the final block, all five nonwords were presented sequentially, and the children were asked to repeat them in the same order. The order of the nonwords was fixed across the three serial recall blocks so that there were two exposures to each item. As the purpose of these recall games was to familiarize the children with the items, no corrective feedback was given. Following these initial familiarization trials, children completed alternating blocks of four free recall test trials and three passive presentation trials. In the first free recall block, children were asked to recall the words they had learned in the preceding presentation trials. Participants were not prompted or corrected by the experimenter and all responses were recorded in writing. Immediately following this block, children were given a passive presentation block in which they were asked to listen to the five nonwords. They were not instructed to repeat the items aloud in these blocks. Immediately following the presentation block, the children completed the next free recall block. This procedure continued until all blocks were completed. In total the verbal pre-exposure stage consisted of 10 exposures

to each of the nonwords and four blocks of free recall test trials (for a maximum free recall score of 20).

*Visual-Verbal PAL.* The start of the second day of testing began with one free recall block in which participants were asked to recall the five nonwords from day 1. Following this, children began the visual-verbal PAL learning stage. This commenced with two presentation blocks in which five abstract visual forms (from Experiment 3.1) were paired with the five nonwords. Following the presentation blocks, the children engaged in five blocks of test trials in which each of the five symbols was presented, and the child was asked to produce the corresponding nonword. Regardless of the accuracy of the response, the correct answer was presented immediately following each trial. This procedure was repeated for each trial across all five blocks. All participants completed all trials, and accuracy per trial and total learning across trials was recorded. The final score was calculated as the total number of correct trials across all five blocks (maximum score of 25). The participant's response was recorded (in writing) following the presentation of each item for use in subsequent error analyses. Following the test trials, a recognition block was administered in which the participants heard each of the five nonwords and were asked to point to the correct picture on the screen. The position of the symbols on the screen was randomized for each trial.

## Results

Mean performance by group and day is displayed in Figure 3.3. Fixed effects for all models are shown in Appendix B.

### *Verbal Learning*

To examine group differences in verbal learning, we ran a linear mixed effects model with subject and item as random effects, and group (dyslexic, control), and block (1-5) as fixed effects. The results revealed that children with dyslexia performed significantly below the control group in verbal learning. There was a main effect of group (OR = 0.30, 95 % CI [0.15, 0.63],  $Z = -3.21$ ,  $p = .001$ ), and block (OR = 1.50, 95 % CI [1.26, 1.80],  $Z = 4.47$ ,  $p < .001$ ), but no interaction between group and block (OR = 0.98, 95 % CI [0.68, 1.40],  $Z = -0.12$ ,  $p = .960$ ). Despite equivalent exposure to the nonwords, children with dyslexia recalled significantly fewer nonwords than typically developing readers.

### *Visual – Verbal PAL*

Consistent with the results of Experiments 3.1 and 3.2, the results of a logistic linear mixed effects model with subject and item as random effects and group and block fixed effects revealed that the dyslexic group performed significantly below the level of the control group in visual-verbal PAL. There was a main effect of group (OR = 0.41, 95 % CI [0.19, 0.88],  $Z = -2.29$ ,  $p = .022$ ) and block (OR = 1.30, 95 % CI [1.13, 1.49],  $Z = 3.74$ ,  $p < .001$ ), but no interaction between group and block (OR = 1.01, 95 % CI [0.77, 1.31],  $Z = 0.05$ ,  $p = .960$ ). These results are perhaps unsurprising given the group differences that emerged in verbal learning, and the robust literature reporting visual-verbal PAL deficits in dyslexia. Our primary question of interest, however, was not

whether a group difference would emerge in visual-verbal PAL, but whether this difference would be greater than expected given the difference in verbal learning. As a preliminary answer to this question, it is interesting to note that the effect of group (dyslexic, control) is similar for verbal learning ( $Z = -3.21$ ) and visual-verbal PAL ( $Z = -2.29$ ), suggesting that visual-verbal PAL deficits are directly proportional to verbal learning deficits.

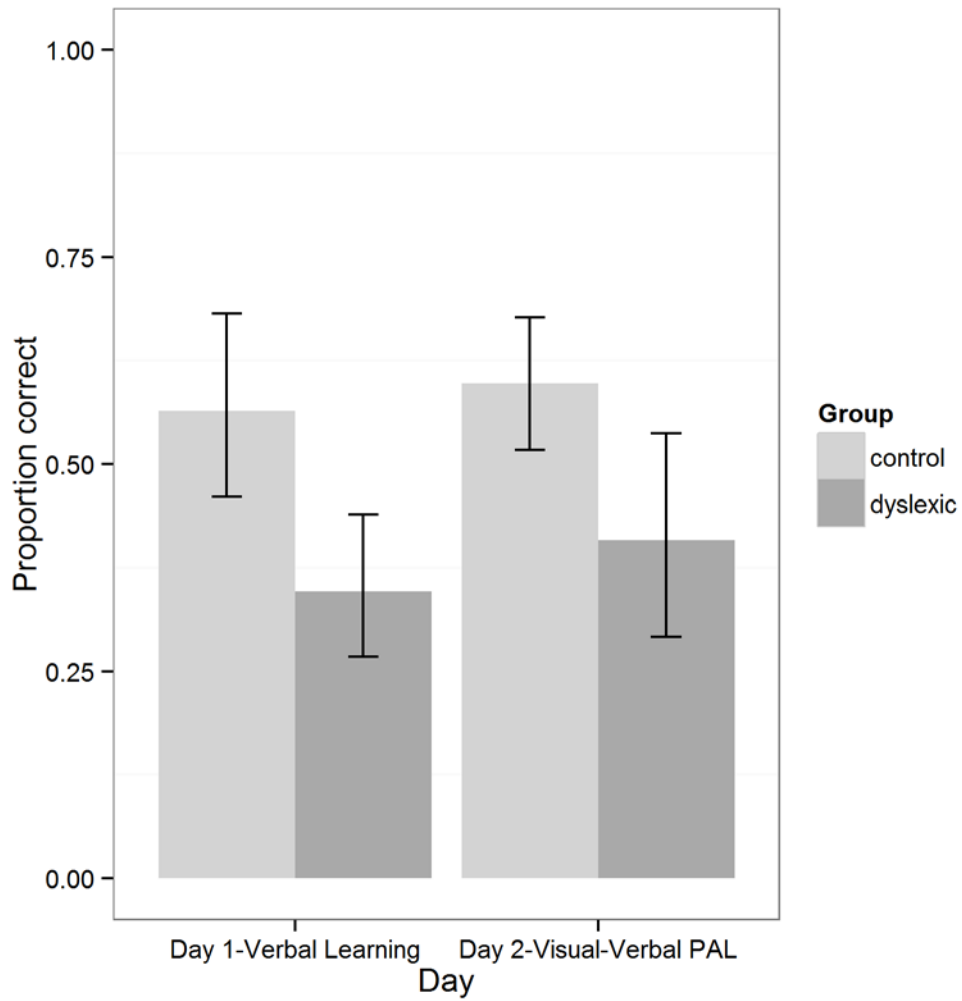
To directly test whether visual-verbal PAL performance is fully accounted for by previous verbal learning performance, we ran a linear mixed effects model with a fully specified random effects structure for subjects and items, and fixed effects for group (dyslexic, control) and verbal learning. We used total verbal learning score (by-item and by-subject) to predict total visual-verbal PAL score (by-item and by-subject). Crucially, this model evaluates the item-specific relationship between verbal learning and visual-verbal PAL, asking whether the extent to which a child learns a nonword predicts the success with which that same nonword is associated with a symbol in visual-verbal PAL. Additionally, the model determines whether this relationship differs between children with dyslexia and typically developing readers. As recommended by Baayen et al. (2008), p-values are reported here based on the normal-approximation of the t-statistic because the significance of model coefficients is not available in lme4 for models with random slopes. Such an approach has been shown to be more conservative than traditional by-subjects and by-items ANOVA (Barr et al., 2012).

The results of the model supported an item specific relationship between verbal learning and visual-verbal PAL (OR = 1.53, 95 % CI [1.24, 1.89],  $t = 3.93$ ,  $p < .001$ ). The extent to which children learned the visual-verbal paired associates was predicted by their success in learning the nonwords in the pre-exposure phase on Day 1. Not only was there a strong predictive relationship between verbal learning and visual-verbal

PAL, but this relationship also held regardless of group membership: group did not emerge as a significant predictor of visual-verbal PAL in the model (OR = 0.58, 95 % CI [0.28, 1.22],  $t = -1.43$ ,  $p = .153$ ). Model comparison showed that a model with verbal learning as the sole predictor of visual-verbal PAL performed equally as well as a model in which group (dyslexic, control) was added as a predictor ( $\Delta\chi^2(1) = 1.756$ ,  $p = .185$ ). In contrast, the addition of verbal learning to a model with group as the sole predictor of visual-verbal PAL significantly improved model fit ( $\Delta\chi^2(1) = 10.45$ ,  $p = .001$ ). Together, these results implicate the vital role of verbal learning in determining visual-verbal PAL performance.

Crucially, although the dyslexic group performed significantly below the control group in both verbal learning and visual-verbal PAL, there was no evidence to support a view of an additive PAL deficit in dyslexia. That is, if visual-verbal PAL deficits reflect specific difficulties with learning to associate two stimuli together, we would expect to find an interaction between group and verbal learning (such that children with dyslexia experience greater difficulty with visual-verbal PAL than expected from their verbal learning scores). However, the interaction between verbal learning and group (OR = 1.13, 95 % CI [0.74, 1.73],  $t = 0.58$ ;  $p = .562$ ) was not significant.

Finally, despite the significant differences in visual-verbal PAL reported above, the dyslexic and control groups demonstrated comparable levels of performance on the recognition task: dyslexic ( $M = 2.79$ ,  $SD = 0.42$ ), control ( $M = 3.29$ ,  $SD = 0.37$ ),  $t(26) = 0.89$ ,  $p = .381$ .



*Figure 3.3.* Proportion correct for the dyslexic and control group in verbal learning and visual-verbal learning in Experiment 3.3. Error bars represent 95% confidence intervals.

## Analysis of Errors

We analyzed the errors made in each phase of the experiment, verbal learning and PAL. Summary data are shown in Table 3.7.

Table 3.7

*Proportion errors by type and group in verbal learning and visual-verbal PAL in Experiment 3.3*

	Dyslexic		Control	
	M	SD	M	SD
<i>Verbal Learning</i>				
Refusals	.63	.04	.53	.06
Phonological errors	.37	.04	.47	.06
Single feature	.79	.06	.93	.03
Multiple feature	.21	.06	.07	.03
Perseverations	.49	.09	.38	.08
<i>Visual-Verbal PAL</i>				
Association	.45	.05	.80	.05
Phonological Errors	.55	.06	.20	.05
Single Feature	.59	.09	.67	.14
Multiple Feature	.41	.09	.33	.14
Perseverations	.42	.09	.44	.14

Verbal learning errors comprised 63% refusals and 37% phonological errors in the dyslexic group, and 53% refusals and 47% of errors in the control group. Since excluding refusal errors from the analysis would leave only one remaining category of errors (i.e. phonological) to be analyzed (because there were only two overall error categories for verbal learning errors), only the subtypes of phonological errors were analyzed. Both groups made more single feature than multiple feature errors, with the dyslexic group committing a higher proportion of multiple feature errors than the control group. However, the results of a log-linear mixed effects model showed that the difference in proportions between groups was not significant (OR = 2.38, 95 % CI [0.68, 8.33],  $Z = 1.36$ ,  $p = .174$ ). Consistent with the error analysis in Experiment 3.2, there was no evidence that the dyslexic group committed a higher proportion of perseveration errors than the control group (OR = 1.17, 95 % CI [0.41, 3.36],  $Z = .28$ ,  $p = .777$ ).

Turning to the PAL phase of the experiment, refusals comprised 12% of dyslexic group errors and 8% of control group errors respectively. After removing these errors, two primary error types remained: association errors and phonological errors. An initial log-linear mixed effects model showed that the dyslexic group committed a higher proportion of phonological errors than the control group (OR = 0.21, 95 % CI [0.10, 0.43],  $Z = -4.21$ ,  $p < .001$ ). Further investigation into the nature of the phonological errors did not reveal a significant difference between the groups in the proportion of single or multiple feature errors (OR = 1.50, 95 % CI [0.21, 10.57],  $Z = 0.40$ ,  $p = .686$ ). Thus it seems that although children with dyslexia made a higher proportion of phonological errors than the control group, when these errors did occur, the likelihood of these errors being near or far from the target word did not differ between groups. Consistent with previous results, there were no differences between

groups in the proportion of perseverations made (OR = 0.80, 95 % CI [0.19, 3.35],  $Z = -0.30$ ,  $p = .763$ ). Finally, there was no evidence for group differences in the proportion of errors continued from the verbal pre-exposure stage (OR = 0.41, 95 % CI [0.12, 1.40],  $Z = -1.42$ ,  $p = .154$ ).

## Discussion

The results of the current experiment support the view that deficits in visual-verbal PAL are a consequence of underlying verbal deficits. When assessed in separate phases, children with dyslexia demonstrated impairments in both verbal learning and visual-verbal paired associate learning. Crucially, however, children with dyslexia did not demonstrate impairments over and above those expected from their verbal learning scores. That is, performance differences in visual-verbal PAL were fully explained by initial rates of verbal learning. This strongly suggests that visual-verbal PAL deficits are a consequence of verbal learning difficulties, and are not specific to the associative demands of the task. Such a finding is in accordance with the results of Experiments 3.1 and 3.2, in which children with dyslexia demonstrated impairments only in those PAL tasks that had a verbal output component.

The error analyses further support these conclusions. On Day 1, both groups showed a similar pattern and extent of phonological errors. This indicates that although children with dyslexia were less efficient than controls (i.e. learned fewer nonwords in the same number of trials), both groups were engaging in the same general process of verbal learning. However, the error patterns diverged quite strikingly on Day 2, with phonological errors comprising the majority of errors in the dyslexic group, and associative errors comprising the majority of errors in the control group. This likely reflects a continued difficulty in phonological form learning that extended into visual-

verbal PAL for the dyslexic group, but not the control group. That the control group made errors that were almost entirely associative in nature (.80) on Day 2 suggests that they were utilizing accurate phonological representations of the novel forms. In contrast, the decidedly greater proportion of phonological errors in the dyslexic group on Day 2 is indicative of a continued difficulty with the acquisition of novel phonological forms. Note, however, that the more balanced proportion of phonological (.55) to associative (.45) errors in the dyslexic group suggests that both phonological and associative learning occurred in the visual-verbal PAL task. Indeed, despite difficulty acquiring the phonological forms, children with dyslexia demonstrated successful learning of the associations on a recognition task. Together, these results provide further support for a view of PAL deficits as specific to the learning of phonological forms.

### **General Discussion**

Three experiments assessed the nature and specificity of PAL deficits in dyslexia. Our goals were twofold: first, to determine whether deficits are specific to verbal or crossmodal mapping demands, and second, to investigate the stage of learning in which deficits emerge. Experiments 3.1 and 3.2 evaluated performance across four conditions, each uniquely characterized by mapping modality (crossmodal, unimodal) and output demand (visual, verbal). Consistent with the literature, we observed robust visual-verbal PAL deficits in the absence of visual-visual PAL deficits, confirming the lack of general associative learning deficits in dyslexia (Messbauer & de Jong, 2003; Vellutino et al., 1975). Crucially, children with dyslexia exhibited deficits only in visual-verbal and verbal-verbal PAL, with no evidence for impairments in visual-visual or verbal-visual PAL. This finding is at odds with a strong theory of impaired

crossmodal associative learning, in which deficits would be expected in both visual-verbal and verbal-visual PAL. Although a direction-dependent theory might provide an explanation for the lack of verbal-visual PAL deficits (i.e., impairments are specific only to visual-verbal PAL because of its shared mapping direction with reading) this account is simply not in accordance with our data. The PAL deficits reported in Experiment 3.1 and 3.2 were not unique to visual-verbal PAL. Instead, deficits emerged in both visual-verbal and verbal-verbal PAL, tasks with a verbal-output demand. This pattern of findings provides unequivocal support for a verbal account of PAL deficits in dyslexia, and mirrors the PAL-reading relationship seen in typically developing readers in Chapter 2.

Further support for this conclusion is provided by the analysis of errors in Experiment 3.2, and indeed, in Experiment 3.3. Although children with dyslexia made more errors overall in both visual-verbal and verbal-verbal PAL than control children, there was no evidence that they committed a higher proportion of associative errors, as would be expected if poor PAL performance results from difficulties with the associative demands of the task. In contrast, children with dyslexia tended to make a higher proportion of phonological errors than controls, a finding in line with Mayringer and Wimmer (2000). There was also some indication that the phonological errors were more severe in the dyslexic group, as indexed by a higher proportion of multiple feature errors. These differences were especially marked in verbal-verbal PAL, arguably because the twin demands of verbal input and verbal output place a greater demand on the phonological system than verbal output alone, as in the visual-verbal condition.

Together, the results of Experiment 3.1 and 3.2 provide support for the phonological nature of PAL deficits; however, they cannot speak directly to the stage of learning at which deficits arise. PAL is a complex task and potentially, the verbal

deficits observed in Experiment 3.1 and 3.2 might arise at one of two phases; learning the phonological form (verbal learning), or associating a visual symbol with the phonological form (associative learning). Additionally, a difficulty at both phases of learning is possible. By separating these two phases within a visual-verbal paired associate learning paradigm, Experiment 3.3 investigated the contribution of phonological form learning and associative learning to PAL performance in children with dyslexia.

Once again, our results were clear. Children with dyslexia learned fewer phonological forms than control children in the verbal learning phase; they were also poorer at mapping visual symbols to these phonological forms, performing less well than controls in the subsequent visual-verbal PAL task. Of course, poor visual-verbal PAL performance may be an expected consequence of verbal learning deficits. Success on any given visual-verbal PAL trial requires children to output the correct phonological form; thus performance hinges critically on the integrity of the new phonological representation. Evidence for a specific difficulty with the associative component of the task would therefore be demonstrated by a finding of visual-verbal PAL deficits that are greater than expected given the initial verbal learning deficits. Against this prediction however, visual-verbal PAL deficits were directly proportional to the extent to which children with dyslexia learned the nonwords in the verbal learning phase; there was no evidence that associative learning placed an additional constraint on PAL performance. In fact, the dyslexic and control groups were equally able to recognize the paired associates, indicating that successful associative learning occurred.

Taken together, the results of our experiments demonstrate that PAL deficits in dyslexia reflect difficulties with the phonological component of the task. However, two

important questions remain: what is indexed by this phonological component, and how does it relate to reading ability? In addressing the first question, it is perhaps useful to distinguish between the initial encoding of a new phonological form vs. its subsequent maintenance. Numerous researchers have proposed that limitations in the phonological loop (the component of verbal working memory responsible for immediate and short term storage of phonological information) impose constraints on children's ability to learn new words in PAL tasks (e.g. Gathercole & Baddeley, 1990; Gathercole, Hitch, Service, & Martin, 1997). This explanation, however, does not sit comfortably with our data as the dyslexic children were as accurate as controls when asked to immediately repeat the new phonological forms (80% vs. 84% for the dyslexic and control groups, respectively<sup>6</sup>). This suggests that group differences in PAL are unlikely to be caused by failure at encoding (for similar findings, see Mayringer & Wimmer, 2000).

In contrast, our data sit more comfortably with the idea that children with dyslexia struggle to maintain the integrity of novel phonological representations over a short period of time, and that this might underpin their subsequent impairments in paired associate learning. It is quite striking that although children with dyslexia showed accurate immediate repetition, the integrity of their representations were not maintained over a relatively short period of time, as evidenced by the phonological distortions produced on test trials. This degradation occurred over the course of only four or five interceding trials despite the presentation of the correct nonword following each test trial, which presumably allowed for updating and adjustment of the phonological representation throughout the task. This is consistent with the idea that children with dyslexia have difficulty establishing stable phonological representations.

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<sup>6</sup> Due to computer coding errors on some of the presentation trials, these figures reflect data only from trials in which both computer data and hardcopy written records were available to ensure validity. However, the general pattern of findings held when examined in the full data set.

The error analyses in Experiments 3.2 and 3.3 also lend support to this conclusion: although children with dyslexia made more phonological errors than controls, they did not make a higher proportion of perseverative errors (although see Mayringer & Wimmer, 2000). That the majority of the phonological errors were new, rather than repeated, strongly suggests that poor performance was not simply a case of having learned incorrect phonological forms. Instead, our results indicate that children with dyslexia experience difficulty with phonological form learning, a conclusion that echoes previous work on PAL (Wimmer et al., 1998; Mayringer & Wimmer, 2000).

We now come to the question of how to orient PAL deficits within the context of reading development and dyslexia. Although our data do not allow us to speak directly to this issue, we shall consider two potential explanations of the PAL-reading relationship. The first account views PAL as a correlate of reading and reading-related skills, while the second grounds PAL in a theory in which phonological form learning plays a direct role in the reading process and its development.

On the first view, PAL and reading may share a correlational relationship due to the influence of a third underlying factor such as phonological processing. For example, the phonemic sensitivity that is crucial to reading development is likely also be crucial to phonological form learning in PAL. In support of this view, concurrent studies have indicated that individual differences in visual-verbal PAL performance can be largely accounted for by phonological processing skill, a finding that holds for both dyslexic and typically developing samples (de Jong et al. 2000; Messbauer & de Jong, 2003; 2006). Additionally, although longitudinal and training studies with PAL are sparse, the few studies that have been reported provide support for this conclusion. For example, Lervåg et al. (2009) found that visual-verbal PAL was not a longitudinal predictor of reading ability when measured in pre-readers, suggesting that the PAL-

reading relationship emerges only once children are literate. Additionally, the findings by de Jong et al. (2000) implicate a direct role for phonological skills in the development of visual-verbal PAL ability: training in phoneme awareness improved visual-verbal PAL performance in kindergartners. If PAL performance relies heavily on the underlying integrity of the phonological system, PAL deficits in dyslexia may be best viewed as a consequence, rather than a cause of the disorder.

On this view, the failure to construct or maintain reliable phonological representations of the nonwords in our PAL tasks may have resulted from a lack of linguistic support from long-term memory, without which, novel representations become highly susceptible to the effects of interference or decay (Hulme, Maughan, & Brown, 1991; Hulme, Roodenrys, Brown, & Mercer, 1995). For example, evidence suggests that as short term memory traces decay, recall success is significantly determined by the availability of representations in long-term memory to aid in the process of redintegration, or reconstruction of these traces (Gupta & MacWhinney, 1997; Hulme et al., 1991; Thomson, Richardson, & Goswami, 2005). Children with dyslexia are generally thought to have phonological representations that are underspecified or inaccurate, which would clearly limit the quality and availability of support from long-term memory (Snowling & Hulme, 1994). Although the current experiment utilized nonword stimuli exclusively, this view is also compatible with the findings in the literature of PAL deficits for words. Arguably, words held in short term memory would be subject to a similar process of decay as outlined above, thus making it difficult for children with dyslexia to hold and maintain the words in memory for use in a PAL task. Of course, we would expect words that are high in frequency or semantic content to be less susceptible to decay than words that are low in frequency, abstract, or phonologically complex, because they enjoy greater support from long-term

memory (Hulme et al., 1997). Indeed, this prediction matches the pattern of findings reported for PAL tasks with words (Elbro & Jensen, 2005; Messbauer & de Jong, 2006; Vellutino et al., 1995).

Although this conceptualization of PAL deficits sits comfortably with the phonological deficit theory of dyslexia, we caution against a view of PAL deficits as equivalent to phonological deficits in dyslexia. Numerous researchers have found that visual-verbal PAL explains unique variance in reading ability, beyond phonological awareness (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Additionally, Wimmer et al (1998) reported visual-verbal PAL deficits in children with dyslexia even though they were matched with controls for phonological awareness. It is, however, possible to reconcile these findings by considering that phonological processing is not a unitary construct; phonological awareness comprises only one component of the phonological system (Wagner & Torgesen 1987; Wagner et al., 1999). Thus the phonological component of verbal-output PAL may index different abilities than those typically tapped by tests of phonological awareness. For example, the learning and establishment of phonological representations in memory likely relies, at least in part, on processes that differ from those involved in the explicit access and manipulation of established phonological representations.

However, the possibility of a more proximal relationship between PAL deficits and dyslexia warrants consideration. Recent theories suggest that phonological form learning plays a specific role in reading acquisition via the formation of novel spelling-linked phonological representations (Elbro et al. 2012; Ranbom & Connine, 2011; Tunmer & Chapman, 2012). For example, when decoding an irregular word such as *island* for the first time, children inevitably produce the phonological form “izland.” Evidence suggests that in skilled readers, this “spelling pronunciation” facilitates

activation of the correct spoken representation in the lexicon, and is subsequently stored and activated alongside the spoken representation in long-term memory (Elbro et al., 2012; Ranbom & Connine, 2011; Venezky, 1999). The ability to utilize variable phonological representations to arrive at the correct spoken pronunciation has been shown to explain unique variance in word recognition skills (Elbro et al., 2012; Tunmer & Chapman, 2012; Vousden & Ellefson, 2012). Thus learning to read may depend on the establishment of novel, orthographically-derived phonological representations, as well as the binding of these spelling pronunciations to spoken pronunciations in memory. Consequently, a deficit in phonological form learning would certainly impede reading acquisition in children with dyslexia. Future research of a longitudinal nature is required to distinguish between this view and the correlational account of the PAL-reading relationship outlined above.

To summarize, the present chapter evaluated the contribution of verbal and associative demands to giving rise to PAL deficits in dyslexia. Contrary to the predictions of the crossmodal hypothesis, children with dyslexia exhibited deficits specific to PAL tasks with a verbal output demand, regardless of whether the mappings were crossmodal or unimodal in nature. Additionally, PAL deficits were shown to be a consequence of difficulties in phonological form learning, rather than difficulties with associative learning. Although there is no doubt that children with dyslexia demonstrate poor learning on any task that requires visual-verbal mappings (e.g. letter learning, reading), our data suggest that the deficits are neither specific to crossmodal mappings, nor do they arise at the level of the association.

## **Chapter 4: The longitudinal relationship between PAL and reading ability**

*This chapter reports a longitudinal study examining the contribution of visual-verbal PAL in pre-readers to the prediction of reading ability at the end of kindergarten. The primary goal of the experiment was to evaluate whether visual-verbal PAL plays a causal role in reading development. The results of a longitudinal model were inconsistent with this hypothesis: PAL in pre-readers did not emerge as a predictor of reading at the end of kindergarten. In contrast, growth in PAL performance was predicted by phonological awareness in pre-readers. The implications of these findings are discussed in regard to theoretical models of the PAL-reading relationship.*

## Introduction

Across the range of abilities, visual-verbal paired associate learning (PAL) shows a robust relationship with concurrent reading skill that cannot be fully explained by variations in children's phonological awareness or rapid automatized naming (RAN) (Hulme et al., 2007; Mayringer & Wimmer, 2000; Vellutino et al., 1975; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). The PAL-reading relationship<sup>7</sup> has often been interpreted as evidence for the role of crossmodal associative learning in reading development, as visual-verbal PAL, like reading, requires the learning of symbol-sound correspondences. Indeed, it has been suggested that crossmodal associative learning represents an independent and causal mechanism involved in reading acquisition (Hulme et al., 2007; Warmington & Hulme, 2012).

Such a mechanism is perhaps best understood according to computational models of reading. In connectionist models, the process of learning mappings from orthography to phonology is computationally explicit: a learning algorithm alters the weight between orthographic inputs and phonological outputs according to the statistical regularity of their co-occurrence (Seidenberg & McClelland, 1989). This process, analogous to visual-verbal PAL, is necessary for accurate reading to occur. In fact, when the learning rate of this mechanism is impeded, reading development is compromised. Likewise, the operation of such a mechanism is implicit in dual-route models of reading, in which accurate reading relies on previously acquired knowledge of both sublexical and lexical orthography-phonology mappings. Potentially, PAL represents the underlying learning mechanism responsible for the acquisition of these mappings.

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<sup>7</sup> In this chapter, the term the "PAL-reading relationship" refers specifically to visual-verbal PAL and reading accuracy (words and nonwords)

Many researchers have speculated that a PAL mechanism plays a pivotal role at the earliest stages of reading development, in which mappings between orthography-phonology are most arbitrary. More specifically, it has been proposed that PAL is a dynamic measure of the learning that underlies variations in letter knowledge (Byrne et al., 2012; Carroll & Snowling, 2004; de Jong & Olson, 2004; Gallagher et al., 2000; Windfuhr & Snowling, 2001). The consistent finding of impaired visual-verbal PAL in children with dyslexia (e.g., Li et al., 2009; Liberman et al., 1982; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Vellutino et al., 1975), coupled with a clear difficulty learning letter-sound mappings early in reading development, is certainly consistent with this view (Carroll & Snowling, 2004; Pennington & Lefly, 2001; Scarborough, 1990; Snowling et al., 2003). More direct evidence comes from de Jong and colleagues (2000), who demonstrated a significant concurrent relationship between PAL and letter knowledge in kindergarten. Interestingly, this relationship held only for a measure of nonword PAL, but not for a PAL task with words, implicating verbal learning in the acquisition of letter knowledge. Recently, Byrne et al. (2012) found that visual-verbal PAL loaded onto the same genetic “print” factor as letter knowledge, orthographic knowledge, and reading. This finding supports the view that PAL indexes learning capacities that also influence reading development. However, it should be noted that the authors did not include alternative measures of PAL (e.g. verbal-verbal), so the extent to which crossmodal associative learning (versus verbal learning) specifically accounts for these findings cannot be determined. Nevertheless, the study provides evidence that there is a shared genetic influence on visual-verbal PAL, letter knowledge, and indeed, orthographic knowledge in general.

Of course, the importance of binding orthography to phonology is unlikely to be confined to the acquisition of letter knowledge. Children continue to be faced with

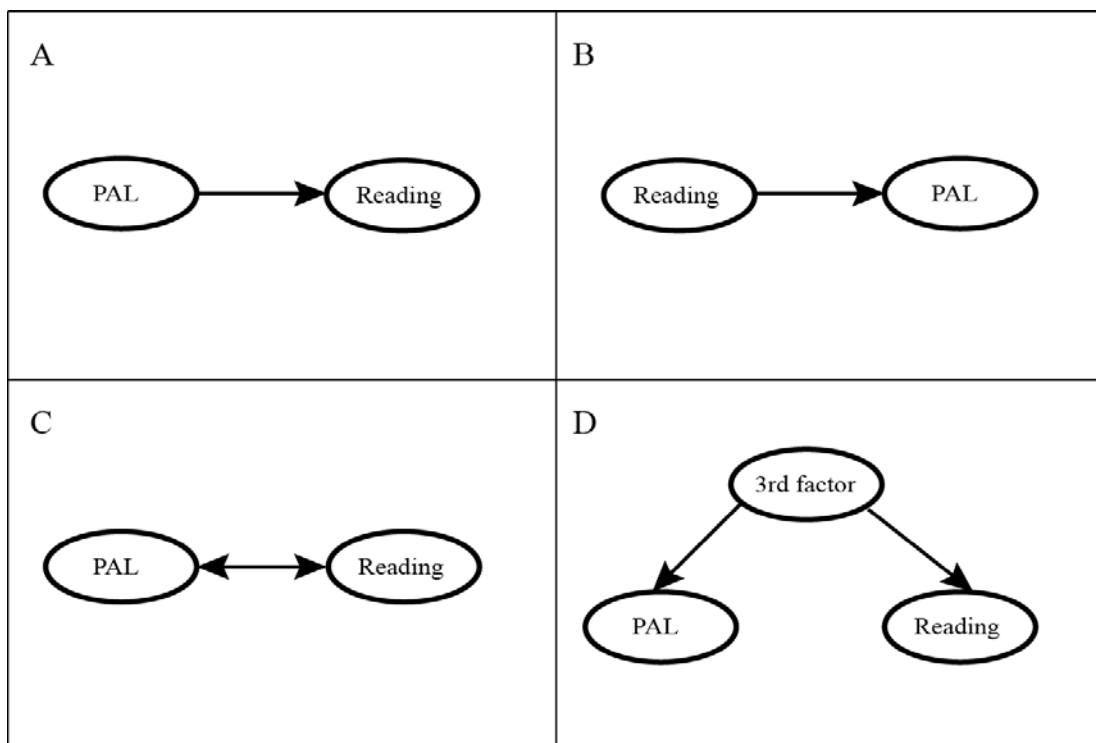
arbitrary orthography-phonology mappings throughout development, at least in irregular orthographies such as English. For this reason, Hulme and colleagues (2007) have argued that PAL plays a particularly important role in irregular word reading. In a study with typically developing children, the authors found that visual-verbal PAL predicted unique variance in irregular word reading, but not nonword reading. This parallels the findings in connectionist models, in which altering the learning parameter has a greater effect on the development of irregular word reading than nonword reading (Harm & Seidenberg, 1999). However, there is also reason to suspect a role for PAL in the acquisition of more systematic whole-word mappings. For example, as children's reading transitions from effortful, systematic decoding, to rapid "sight word" reading, this likely depends on the formation of larger-grain mappings between orthography and phonology (Ehri, 1998; Mayringer & Wimmer, 2000). Thus, the influence of PAL on reading ability may extend far beyond the initial learning of letter-sound correspondences to the acquisition of orthographic knowledge.

Although there is strong evidence for a concurrent relationship between PAL and reading skill, and much speculation as to the role of PAL in reading development, the nature of this relationship remains underspecified. As highlighted by Figure 4.1, there are several theoretical models that could account for the correlation between PAL and reading. Panel A shows a causal model in which PAL leads to growth in reading ability. Although this model aligns most closely with the speculation in the literature, the PAL-reading relationship could potentially run in the reverse direction, with the development of reading skills exerting an influence on PAL, as shown in Panel B. On this view, the development of reading<sup>8</sup> alters the language processing system, which in turn influences the manner and success with which children perform a PAL task. Note

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<sup>8</sup> Note that the term *reading* is used throughout this chapter as shorthand for the cognitive changes brought about by learning to read.

that this model predicts that the PAL-reading relationship should emerge alongside literacy development. A third possibility, shown in Panel C, is that the PAL-reading relationship is reciprocal, with both skills exerting an influence on each other. A final possibility, shown in Panel D, is that the correlation between PAL and reading is driven by a third underlying variable that exerts a causal influence on both PAL and reading. In the current study, we utilized a longitudinal approach to investigate the PAL-reading relationship. Although such a design cannot establish causality (for that, training studies are necessary), it allows for a clearer understanding of the relationship between variables over time.



*Figure 4.1.* Models of causal relationships underlying observed correlation between PAL and reading

To date, only one study has examined the PAL-reading relationship longitudinally. Lervåg and colleagues (2009) evaluated the contribution of visual-verbal PAL to the prediction of reading ability in Norwegian, starting when children were pre-readers. The authors found that whereas RAN, phonological awareness, and letter knowledge predicted growth in reading over time, PAL did not emerge as a longitudinal predictor of reading skill. This finding is inconsistent with results from studies (including the results from Chapter 2) showing that visual-verbal PAL predicts unique variance in reading ability above and beyond both phonological awareness and RAN when measured concurrently (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). The discrepancy in findings indicates that PAL may be a correlate of reading ability, rather than a cause. However, it is possible that the study by Lervåg and colleagues failed to find evidence for a longitudinal influence of PAL on reading ability because it was conducted in Norwegian, a highly transparent orthography. Given the evidence from Hulme and colleagues (2007) that PAL predicts variance in irregular word reading, but not nonword reading, it is plausible that PAL may play a stronger role in reading development in an irregular orthography such as English.

There were two overarching aims of the current chapter. First, we sought to adjudicate between the theoretical models of the PAL-reading relationship presented in Figure 4.1. To do so, we measured visual-verbal PAL in pre-readers at the start of kindergarten, and again at the end of the first year of literacy instruction. We also measured letter knowledge, phonological awareness, and RAN to determine if PAL explains unique variance in reading skill beyond these well-established predictors of reading development. Including these measures allowed for a direct comparison

between our longitudinal model and the models of the concurrent PAL-reading relationship reported by Warmington and Hulme (2012) and in Chapter 2 of this thesis.

A second aim of the study was to evaluate the relationship between PAL and pre-literacy skills. We were particularly interested in the relationship between PAL and measures of phonological awareness, verbal short term memory (i.e., nonword repetition, digit span), and long term memory for phonological forms (as indexed by expressive vocabulary). Following from the results of Chapters 2 and 3 suggesting that PAL depends on the ability to establish novel representations of phonological forms, we hypothesized that PAL would demonstrate a relationship with phonological awareness and vocabulary. In contrast, we did not expect a strong relationship between PAL and verbal short term memory, as Chapters 2 and 3 indicated that variations in PAL performance did not stem from differences in immediate memory for novel phonological forms. On the other hand, the literature implicating verbal short term memory in vocabulary development would predict a relationship between PAL and verbal short term memory (at least when measured by nonword repetition), if PAL is indeed a measure of phonological form learning (for review, see Gathercole 2006). We also examined the relationship between PAL and nonalphanumeric RAN, as it has been proposed to reflect the ability to learn arbitrary symbol-sound associations (Manis et al., 1999). However, given more recent evidence showing that visual-verbal PAL predicts variance in reading ability independent from RAN, and the modest correlations reported in the literature (including Chapter 2 of this thesis), we did not expect to observe a strong relationship between PAL and RAN (Lervåg, et al., 2009; Poulsen et al., 2012; Warmington & Hulme, 2012). Finally, we were interested in the relationship between letter knowledge and PAL, as it has been proposed that letter knowledge measures the outcome of previous PAL (Byrne et al., 2012; Carroll & Snowling, 2004; Gallagher et

al., 2000). If this were the case, we would expect the two measures to be strongly correlated.

Before moving on, it should be noted that the data reported in this chapter come from a large database that allows for a number of questions to be addressed concerning the early stages of learning to read. For the present purposes however, we consider only the questions (outlined above) that are directly related to the focus of this thesis.

## **Method and Procedure**

### **Participants**

Participants were recruited from kindergarten classrooms in four schools serving middle and upper-class catchment areas in Littleton, Colorado. Consent forms were sent home with all children in eligible classrooms. Consent forms were not sent home with children with previously identified special educational needs or non-native English speakers. Children for whom consent was obtained were tested at two time points, once at the start of the academic year in September, and once at the end of the academic year in late April. A total of 73 children participated in the study at both time points. However, because we were interested in the potential causal influence of literacy acquisition on PAL performance, we only analyzed data from children who were not reading at Time 1. Pre-readers were defined as children who could read no more than three words on the Time 1 reading measure (see below for details). This criterion led to a final sample of 62 children (31 boys, 31 girls), with a mean age of 6 years, 2 months at the start of the study ( $SD = 4$  months).

Children were tested individually in a quiet room in their school. The following measures were administered over three sessions, each lasting approximately 15 minutes.

*Visual-Verbal PAL.* In this test, children were asked to learn the associations between three novel symbols and three CVC nonwords. A different set of symbols and nonwords was used at Time 1 and Time 2 so that the stimuli were novel at both time points (for stimulus-response pairings, refer to Appendix A). The abstract symbols were chosen from extinct written languages (e.g., Akkadian) and matched for difficulty of verbalization and ease of drawing. These ratings were obtained from pilot testing in which adults rated the ease/difficulty with which they could assign a verbal description or label to each item. Symbols were chosen if they were rated as difficult to verbalize. All nonwords were chosen from the ARC Nonword Database (Rastle et al., 2002). Each stimuli set was made up of phonotactically legal closed syllable CVC (consonant-vowel-consonant). The nonwords within each set at Time 1 and Time 2 differed in the beginning and ending consonant as well as the vowel sound so that each nonword was as distinct from the others as possible. At the start of the procedure, children were told that they were going to learn the names of some symbols from an “alien alphabet.” Each of the symbols was printed in black ink on a white 3”x 5” flashcard. The testing consisted of two presentation blocks and five test blocks. The symbol cards were shuffled between every trial so that the order of presentation was random. The procedure began with two presentation trials in which the experimenter showed the child each of the symbols, one at a time, and named them aloud for the child (e.g. “This is *mib*”). In the first presentation block the child was asked to repeat the name of the symbol to ensure that the child could accurately reproduce the nonword. If the pronunciation was incorrect, the experimenter said, “that’s not quite right” and then repeated the correct nonword. In the second presentation block, the child was simply asked to watch the presentation of each symbol and try to learn its name. Following the presentation blocks, the children completed six test blocks with feedback. In each trial,

the experimenter presented the child with one symbol card and asked the child for the name of the symbol. Participant responses were recorded. If correct, the experimenter said, “yes, that’s correct.” If incorrect, the experimenter said “that’s not quite right” and then repeated the correct word. All participants completed all six test blocks. Correct responses were recorded per trial and summed for a total score out of 18.

*Letter Knowledge.* To assess letter knowledge children were presented with a sheet containing all 26 letters of the alphabet in a random order. The letters were printed in size 42 Veranda font in black ink. The children were first instructed to name each letter on the sheet. If the child gave the letter sound, the experimenter would say “that is a sound the letter can make, but do you know the name of the letter?” Correct answers were added for a raw subtest score out of 26. Following this, the children were asked to go through the list again and give the sound of each letter. If the child gave the letter name, the experimenter said “that is the name of the letter, but do you know the sound it makes?” The correct answers were added to give a subtest score out of 26. A total letter knowledge score was computed by adding up the letter name and letter sound subtests for a total score out of 52. Both hard and soft sounds for g and c were accepted as correct answers.

*Phonological Awareness.* The Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP) (Wagner et al., 1999) was used as a measure of phonological awareness. The Elision subtest requires participants to delete segments from words. Early items require a syllable to be deleted, whereas later items require a phoneme to be deleted (e.g., “Say *bold* without the *b*”). There are 20 items in this subtest.

*Nonword Repetition.* The Nonword Repetition subtest from the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999) was used as a measure

of nonword repetition. Children must listen to and repeat nonwords varying in length from one to six syllables. The total score is the number of nonwords correctly repeated out of 18.

*Memory for Digits.* The Memory for Digits subtest from the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999) was used as a measure of forward digit span. Children must listen to and repeat a sequence of digits ranging from two to eight digits in length. The total score is the number of sequences repeated correctly out of 21.

*Rapid Automatized Naming.* The object and color naming subtests of the CTOPP were administered as an assessment of Rapid Automatized Naming (RAN) (Wagner et al., 1999). In each subtest, six colored squares (e.g., black, red, green, blue, brown, yellow) or six common objects (e.g., pencil, chair, fish, key, star, boat) are repeated six times throughout a 36-item matrix arranged in four rows of nine items. Children must name the items in the array sequentially, starting at the top of the page from left to right as quickly as possible. Two different arrays are presented for each subtest. The total naming time (in seconds) across both arrays is measured.

*Expressive Vocabulary.* The Expressive Vocabulary subtest from the Clinical Evaluation of Language Fundamentals (CELF-4; Semel, Wiig, & Secord, 2003) requires children to name pictures of people, objects, and actions.

*Regular, Irregular, and Nonword Reading.* The Castles and Coltheart Reading Test 2 (CC2; Castles et al., 2009) was administered at Time 1 to screen for pre-readers, and at Time 2 as a measure of reading ability. This test requires children to read aloud 40 regular words (e.g., bed, take), 40 irregular words (e.g., cough, island), and 40 nonwords (e.g., pofe, delk) of varying difficulty. The items are presented on flashcards with the regular, irregular, and nonwords intermixed in a list of 120 items. The order of

the items is fixed and increases in difficulty. Testing is discontinued for a specific category if the child makes five consecutive errors in that category of items. If a stopping point is reached in one category, testing continues in the remaining categories until a child reaches the stopping point for each category (or reads all of the words in each category). The score is the total correct out of 40 for each category.

*WORD basic reading.* The Wechsler Objective Reading Dimension (WORD) is a standardized untimed measure of single word reading (Wechsler, 1993). The score is the number of words read correctly out of 50. This measure was only administered at Time 2.

## **Results**

Descriptive statistics at both time points are displayed in Table 4.1. The reliabilities for standardized measures (taken from test manuals) are generally very good. A reliability measure for the CC2 reading test was not available, but the subtest scores correlated highly with the standardized WORD Basic Reading assessment ( $r = .76-.86$ ), indicating good reliability. The reliability of PAL was assessed by calculating Cronbach's coefficient alpha at Time 1 ( $\alpha = .83$ ) and Time 2 ( $\alpha = .84$ ), both of which indicated good reliability. For letter knowledge, reliability at Time 1 was assessed by the correlation between letter names and letter sounds ( $r = .76$ ). Reliability was not calculated at Time 2, as letter knowledge was at ceiling. Although we had hoped to examine the effect of PAL on growth in letter knowledge, the ceiling effect at Time 2 precluded this analysis. We therefore focused our subsequent analyses exclusively on the prediction of reading ability, using letter knowledge at Time 1 as an autoregressor.

A series of paired-samples *t*-tests established that there was significant growth in every variable over time. Although the children were still in the beginning stages of reading at Time 2 (indicated by the low raw scores on the reading measures), the children were performing in the average range for their age according to the norms for both reading tests administered: WORD ( $M = 96.15$ ,  $SD = 10.85$ ); CC2 (*z* scores) regular ( $M = -0.67$ ,  $SD = 0.76$ ), irregular ( $M = -0.70$ ,  $SD = 0.96$ ), nonword ( $M = -0.57$ ,  $SD = 0.68$ ).

Table 4.1

*Descriptive statistics (raw scores) at Time 1 and 2 (n = 62)*

	Reliability	Time 1		Time 2	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
PAL	see text	5.79	3.83	8.82	4.17
Letter Knowledge	see text	36.34	10.99	48.29	2.85
PA	.89	3.00	2.16	6.42	3.34
Nonword Repetition	.78	8.88	2.84	10.20	2.54
Memory for Digits	.77	9.34	2.11	10.87	2.20
RAN objects	.79	106.67	23.49	98.46	24.10
RAN colors	.82	109.41	29.26	99.60	27.43
Expressive Vocabulary	.83	24.19	8.19	31.20	8.01
CC2 Regular	see text			6.41	7.50
CC2 Irregular	see text			3.21	4.11
CC2 Nonword	see text			2.89	5.18
WORD Basic	.95 <sup>a</sup>			12.13	6.47

*Notes.* All reliabilities are Cronbach's alpha, except where otherwise indicated. CC2 = Castles and Coltheart 2; PA = phonological awareness; PAL = paired associate learning; RAN = rapid automatized naming; WORD = Wechsler Objective Reading Dimension. <sup>a</sup>Split-half reliability

The correlations between predictors at both time points are displayed in Table 4.2. Letter knowledge, phonological awareness, nonword repetition, digit span, and expressive vocabulary all correlated moderately at Time 1. However, none of these measures correlated with RAN objects or RAN colors at Time 1. PAL at Time 1 showed moderate correlations with RAN objects and expressive vocabulary, but was unrelated to the other cognitive measures.

At Time 2, the reading measures correlated with PAL, letter knowledge, phonological awareness, and digit span. PAL at Time 2 correlated moderately with phonological awareness, expressive vocabulary, and two of the reading measures (WORD Basic, nonword reading). Interestingly, although PAL correlated with expressive vocabulary at both time points, it did not correlate with nonword repetition or digit span. Additionally, it is worth noting that, with the exception of a moderate correlation between PAL and RAN objects at Time 1, all other correlations (both concurrent and longitudinal) between the alphanumeric RAN measures and PAL were not significant.

Most relevant to our hypotheses are the correlations between Time 1 and Time 2 measures. Although phonological awareness was unrelated to PAL at Time 1, it demonstrated a moderate longitudinal correlation with PAL at Time 2. Crucially, despite the concurrent correlation between PAL and reading measures at Time 2, the longitudinal correlations between PAL and reading measures were not significant.

Table 4.2

*Correlations between variables at Time 1 and Time 2 (correlations between time points shown in shaded text)*

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.
<i>Time 1.</i>																				
1. PAL	-	.23	.04	.13	.14	-.29*	.09	.29*	.29*	.15	.20	-.05	.05	-.18	-.03	.11	.07	.06	.09	.19
2. Letter Knowledge		-	.43**	.33**	.34**	-.16	.03	.48**	.33**	.35**	.42**	.13	.39**	-.10	.13	.33*	.37**	.35**	.29*	.43**
3. Phonological Awareness			-	.38**	.31*	-.12	-.14	.40**	.32*	.30*	.57**	.12	.37**	-.26*	.02	.53**	.52**	.45**	.53**	.49**
4. Nonword Repetition				-	.41**	-.03	.02	.38**	.25	.27*	.27*	.40**	.45**	-.09	-.01	.22	.42**	.44**	.42**	.43**
5. Digit Span					-	-.20	-.14	.26*	.17	.14	.21	.50**	.68**	-.24	-.10	.18	.22	.22	.19	.26*
6. RAN Objects						-	.52**	-.18	-.11	-.17	-.02	.13	.12	.56**	.64**	-.19	.13	.17	.03	.07
7. RAN Colors							-	.06	.13	-.21	.08	.01	.04	.28*	.51**	.05	.11	.07	.09	.13
8. Expressive Vocabulary								-	.27*	.16	.19	.04	.33**	-.06	.05	.68**	.12	.15	.08	.19
<i>Time 2.</i>																				
9. PAL									-	.17	.28*	.16	.20	-.02	.11	.28*	.21	.13	.27*	.26*
10. Letter Knowledge										-	.52**	.10	.26*	-.26*	-.08	.25	.37**	.20	.33*	.36**
11. Phonological Awareness											-	.07	.35**	-.16	.12	.29*	.52**	.40**	.52**	.58**
12. Nonword Repetition												-	.43**	-.10	-.04	-.06	.24	.25	.17	.22
13. Digit Span													-	-.12	.15	.26*	.44**	.43**	.30*	.47**
14. RAN Objects														-	.64**	-.15	-.11	-.01	-.17	-.18
15. RAN Colors															-	.02	.19	.23	.12	.16
16. Expressive Vocabulary																-	.11	.11	.13	.15
17. CC2 Regular Words																	-	.87**	.84**	.87**
18. CC2 Irregular Words																		-	.70**	.86**
19. CC2 Nonwords																			-	.76**
20. WORD Basic Reading																				-

*Notes.* p < .05\*; p < .01\*\*

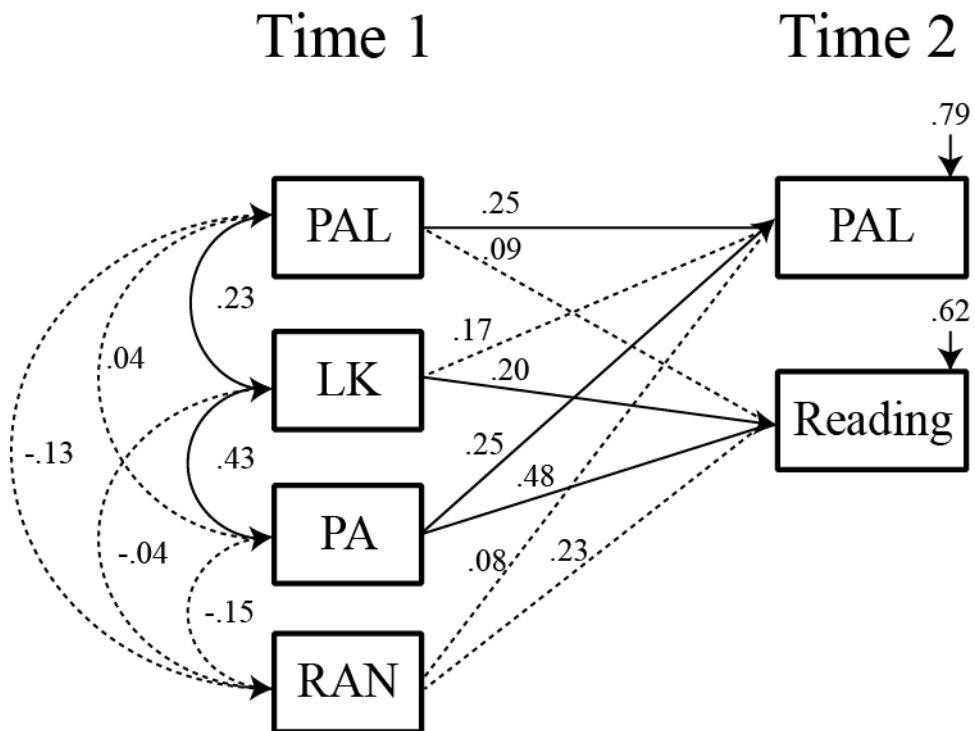
*Evaluating the direction of the PAL-reading relationship*

To assess the direction of the PAL-reading relationship, we constructed a path model in Mplus (version 5.21, Muthén & Muthén, 2009). This approach is advantageous because it allows for simultaneous multiple regression on more than one dependent variable<sup>9</sup>. Before running the model, composite variables were formed for both RAN and reading by summing the *z*-scores of the component measures for all participants (all correlations between component measures were significant at the  $p = .01$  level). The RAN composite was derived from RAN colors and RAN objects, and the reading composite from the WORD Basic and the irregular, regular, and nonword reading scores from the CC2. To assess the direction of the PAL-reading relationship, we constructed a model with PAL, letter knowledge, phonological awareness, and RAN at Time 1 as predictors of PAL and reading at Time 2. By doing so, we simultaneously evaluated the contribution of PAL to growth in reading and the contribution of reading-related skills (i.e., letter knowledge, phonological awareness, and RAN) to growth in PAL, while also accounting for the autoregressive effects of both outcome variables at Time 1. Note that because the children were pre-readers at Time 1, letter knowledge was used as the autoregressor for reading. Additionally, because it has been proposed that PAL is particularly important for irregular word reading (Hulme et al., 2007), we ran alternative versions of the model with irregular, regular, and nonword reading evaluated separately. In all cases, the models were identical regardless of whether we used the composite reading score, or irregular, regular, or nonword reading. For this reason, we report only the model with the composite reading score.

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<sup>9</sup> It should be noted that this technique was utilized to test specific predictions regarding the longitudinal relationship between observed variables. In contrast to the typical use of structural equation modelling to determine causal models of reality, our analyses sought to test whether specific predictive relationships deviated significantly from zero. Thus the model is best understood as a description of our data rather than a theoretical model of reading development.

The model allowed for correlations between predictors and all possible paths from the predictors (PAL, phonological awareness, and RAN) to reading (word accuracy, word fluency, and nonword fluency). The outcome variables were not allowed to correlate in the model. Because some variables demonstrated mild to moderate deviations from normality, we used robust maximum likelihood estimation techniques (MLR in Mplus). The resulting model is shown in Figure 4.2, and provides a good fit to the data. Paramount to our hypotheses, PAL did not emerge as a longitudinal predictor of reading ability ( $p = .345$ ). Instead, both letter knowledge ( $p = .025$ ) and phonological awareness ( $p < .001$ ) made independent contributions to reading development. The contribution from RAN to reading was marginal, although not in the predicted direction ( $p = .057$ ). In contrast, growth in PAL was predicted by phonological awareness ( $p = .017$ ), even after accounting for the autoregressive effect of PAL at Time 1 ( $p = .009$ ). Neither letter knowledge ( $p = .110$ ) nor RAN ( $p = .539$ ) predicted growth in PAL, however. This finding supports the hypothesis that PAL performance depends crucially on phonological skills. However, given the lack of correlation between PAL and phonological awareness at Time 1 ( $p = .724$ ), it also suggests that phonological skills influence PAL performance only once children begin to read.



*Figure 4.2.* Longitudinal path analysis model predicting PAL and reading accuracy at Time 2 from PAL = Paired associate learning, LK = letter knowledge, PA = phonological awareness, and RAN = rapid automatized naming at Time 1. Double-headed arrows represent correlations between predictors. Single-headed arrows represent predictive relationships between the predictor variables on the outcome variables. Solid paths represent statistically significant predictive relationships. Dashed paths represent non-significant predictive relationships. The arrows and values above the dependent variables represent the proportion of variance not explained by the predictors in the model, or the residual variance. All values presented in the model are standardized. Fit indices are as follows:  $\chi^2(1) = 0.01$ ,  $p = .918$ , RMSEA = 0.00 [90% CI: .00-.13], SRMR = 0.00, CFI = 1.00.

The aim of the model presented above was to test whether the robust finding in the concurrent literature – that PAL predicts reading independently from phonological awareness and RAN – would hold longitudinally. The results were clear: PAL did not predict unique variance in reading longitudinally. Because we were interested in growth in skills over time, we also included the autoregressor for PAL and reading (here, letter knowledge) in the model. Arguably however, this is a very stringent test of the longitudinal contribution of PAL to reading. Including letter knowledge as a predictor at Time 1 could potentially account for the failure of PAL to predict reading longitudinally. If letter knowledge is essentially a crystallized measure of PAL, then the contribution of PAL to reading may already be subsumed by letter knowledge. By forcing the measures to compete in the model, it is possible that only the stronger (or more reliable) of these predictors reached significance in the model. However, it should be noted that PAL and letter knowledge demonstrated only a moderate relationship at Time 1 in our model ( $r = .23$ ). Nevertheless, we constructed an alternative model in which only PAL, phonological awareness, and RAN were entered as predictors of reading ability to address the possibility that PAL failed to predict reading due to the inclusion of letter knowledge in the model. Even in this less conservative model, however, PAL did not emerge as a predictor of reading skill ( $\beta = .14, p = .130$ ).

#### *The relationship between PAL and other cognitive abilities*

In a final set of analyses we set out to explore the strength of the relationship between PAL and other cognitive predictors of reading, and to examine potential changes in these relationships over time. This was an exploratory analysis and thus the conclusions that can be drawn from it are limited. Nevertheless, the information

presented is useful in addressing the hypotheses set out in Chapters 2 and 3 regarding the underlying abilities tapped by visual-verbal PAL.

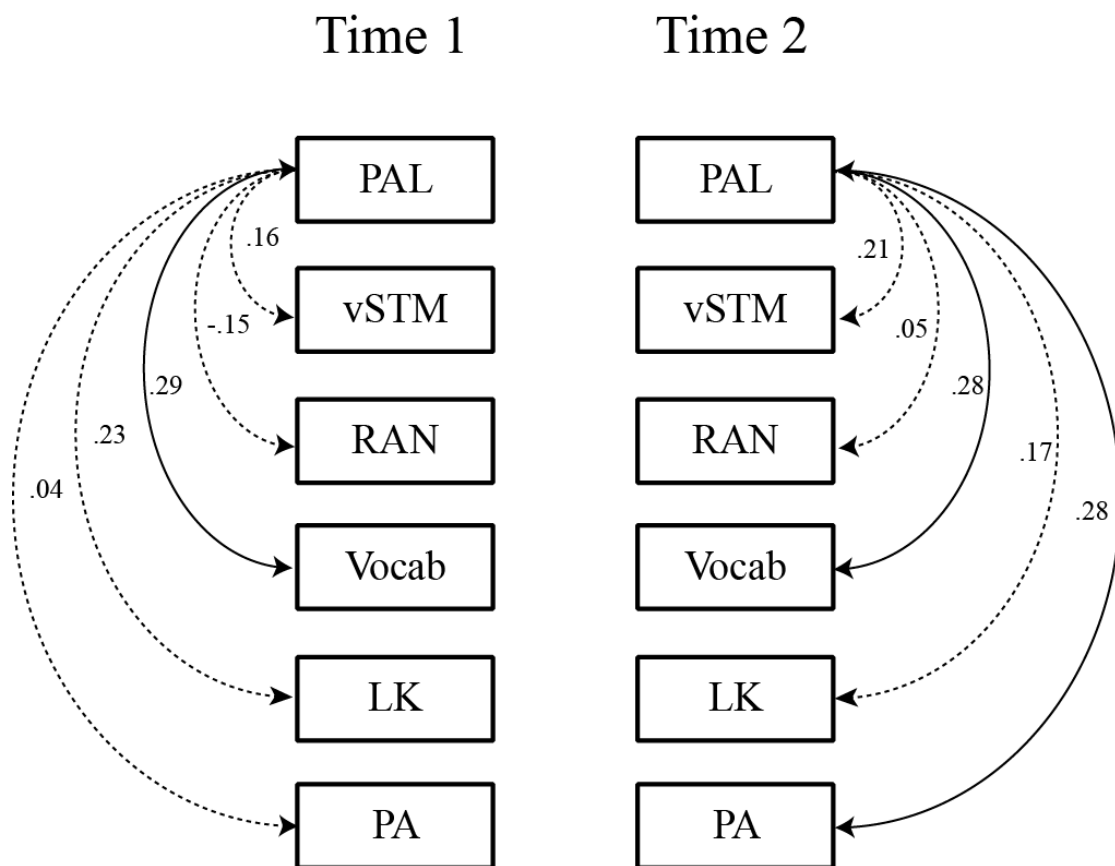
We first ran a simultaneous path analysis in MPlus to examine the concurrent predictors of PAL performance at Time 1 and Time 2. We ran a model at both time points with verbal short term memory (vSTM), RAN, vocabulary, letter knowledge, and phonological awareness as predictors of PAL. Note that we do not report a model predicting *growth* in PAL over time because the findings were consistent with those summarized in Figure 4.2; only phonological awareness predicted growth in PAL, even if vSTM and vocabulary were included. For simplicity, composite measures were derived for vSTM (i.e. nonword repetition, digit span) and RAN (i.e. objects, colors). Together, the predictors accounted for only 13.5% of variance in PAL at Time 1, and 14.1% of variance in PAL at Time 2. At Time 1 none of the variables could predict unique variance in PAL<sup>10</sup>. At Time 2, vocabulary was the only unique predictor of PAL ( $\beta = .22, p = .044$ ). Because the variance in PAL predicted by these models was modest, and the unique contribution of the predictors absent to minimal, we focus subsequently on the correlations between PAL and the cognitive predictors at Time 1 and Time 2.

Figure 4.3 shows the correlations between PAL and the cognitive measures of interest. At Time 1, PAL demonstrated a relationship with vocabulary ( $p = .021$ ), and a marginal relationship with letter knowledge ( $p = .068$ ) but not with vSTM ( $p = .215$ ), RAN ( $p = .309$ ), or phonological awareness ( $p = .759$ ). At Time 2, the relationship with vocabulary remained ( $p = .028$ ), and was similar in strength to the correlation at Time 1. At Time 2, PAL was not correlated with vSTM ( $p = .105$ ), RAN ( $p = .737$ ), or letter knowledge ( $p = .197$ ); however ceiling effects in letter knowledge at Time 2 limit the

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<sup>10</sup> Note that we also ran hierarchical regression models, however we will not discuss these models in-depth, as no variables could predict unique variance beyond any other variables at Time 1 or Time 2 (with the exception of vocabulary at Time 2, discussed above)

conclusions that can be drawn from the lack of correlation with PAL. Notably, a significant relationship between PAL and phonological awareness emerged at Time 2 ( $p = .030$ ). However, the difference in the correlation between PAL and phonological awareness at Time 1 versus Time 2 failed to reach significance ( $z = -1.48, p = .069$ ) on Steiger's  $z$  test of the difference between dependent correlations (Steiger, 1980).



*Figure 4.3.* Correlations between PAL and other cognitive predictors of reading ability at Time 1 and Time 2. PAL = paired associate learning; vSTM = verbal short term memory; RAN = rapid automatized naming; Vocab = expressive vocabulary; LK = letter knowledge; PA = phonological awareness. Double-headed arrows indicate correlations between measures. Solid arrows represent statistically significant relationships.

## Discussion

The primary aim of Chapter 4 was to determine the direction of the PAL-reading relationship by evaluating growth in PAL and reading over the critical period in which formal literacy instruction begins. Children were first assessed across a range of cognitive measures at the start of kindergarten, before they were able to read. By measuring these skills in pre-readers, we were able to speak more closely to their causal role in reading development. The crucial question was whether PAL measured at the start of kindergarten (Time 1) would predict reading ability at the end of kindergarten (Time 2).

Our results on this question were clear: PAL did not emerge as a longitudinal predictor of reading ability. Not only was PAL unable to predict growth in reading in a model with phonological awareness, RAN, and letter knowledge as predictors, but it also failed to emerge as a predictor in a less conservative model in which the autoregressive effect of letter knowledge was not included. This leaves little doubt as to the correlational nature of the PAL-reading relationship; whereas PAL did not predict reading longitudinally, it did demonstrate a concurrent relationship with reading at Time 2. This concurrent correlation is consistent with other findings, including our own from Chapter 2 (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001).

These results are in line with the Norwegian latent variable study by Lervåg et al. (2009), in which PAL in pre-readers did not predict reading longitudinally. Importantly, our cross-linguistic replication shows that PAL does not play a causal role in reading, even in highly irregular orthographies such as English, in which the ability to learn arbitrary mappings may be more crucial (Hulme et al., 2007; Lervåg et al., 2009). In line with Lervåg and colleagues, we found that reading was predicted by

phonological awareness, letter knowledge. However, whereas Lervåg and colleagues found that RAN was a significant predictor of reading ability after three months of literacy instruction, we did not replicate this result.

We can only speculate as to why RAN did not predict reading in our model. Whereas Lervåg et al. (2009) included measures of both reading fluency and accuracy, we only included measures of reading accuracy, which tend to show a weaker relationship with RAN than measures of fluency (e.g., Bowers, 2001; Schatschneider et al., 2004; for review, see Kirby, Georgiou, Martinussen, & Parrila, 2010). Thus, we might have expected a weaker relationship than that reported by Lervåg and colleagues. Additionally, differences between the English and Norwegian orthography may provide some explanation for our results. In contrast to the highly regular Norwegian orthography, English is an opaque orthography characterized by irregular sound-symbol correspondences. RAN is generally thought to exert a greater influence as reading becomes more skilled and fluent, which occurs on a faster time course in transparent compared with opaque orthographies (Byrne et al., 2009; Caravolas et al., 2013; Vaessen et al., 2010). The children in our study were only at the very beginning stages of effortful alphabetic decoding at the end of kindergarten. It must be stressed, however, that despite their low reading scores, performance was at the expected level for children of this age. Perhaps the influence of RAN would have emerged if measured at a later time point when children were more skilled readers.

Although these explanations may account for the weaker relationship between RAN and reading in our study compared with the study by Lervåg and colleagues, there is no obvious explanation for why the correlation between RAN and reading was not in the expected direction. In the initial assessment of the variables themselves, it was noted that the RAN measures were normally distributed, whereas the reading measures

exhibited deviations from normality (i.e., positive skew). However, these deviations from normality motivated our choice to use robust maximum likelihood estimation techniques (MLR) when constructing the model, which do not assume normality of data and have been shown to be robust to non-normality (Yuan & Bentler, 2000). It is not uncommon for longitudinal studies to report similar deviations from normality in reading measures with young children, and in these cases robust estimation techniques are typically used (Lervåg et al., 2009; Lervåg & Hulme, 2009; Lonigan et al., 2000). Despite these similarities in the approach to data analysis, it seems that in our sample variations in RAN at Time 1 did not explain individual differences in reading at Time 2.

A novel aim of this study was to examine developmental changes in PAL over the first year of literacy instruction. By including PAL at both time points, we were able to assess the contribution of pre-literacy skills to growth in PAL performance over time. The results revealed that growth in PAL was predicted by phonological awareness at Time 1, even after accounting for the autoregressive effect of earlier PAL performance. This finding fits well with the results of Chapter 2 and 3 of this thesis, in which the phonological learning component of PAL tasks was found to account for the relationship with reading ability. Interestingly, however, a follow-up examination of the correlations between PAL and phonological awareness revealed that although the measures were related longitudinally (and concurrently at Time 2), they were unrelated at Time 1. We will return to the implications of this finding later in the discussion.

A final issue addressed by this study was the extent to which PAL is related to other cognitive abilities. A primary question of interest was whether PAL and letter knowledge would demonstrate a strong relationship, as it has been proposed that PAL underlies variations in letter knowledge (Byrne et al., 2012; Gallagher et al., 2000; McBride-Chang & Suk-Han, 2000; Windfuhr & Snowling, 2001). We originally

planned to examine whether PAL predicts growth in letter knowledge over the kindergarten year; however, ceiling effects in letter knowledge at Time 2 prevented this analysis. Our results are thus limited in the extent to which they can speak to the role of PAL in the development of letter knowledge. For this, a longitudinal study commencing earlier in the pre-school years would likely prove more fruitful. Notwithstanding this, in the current study, PAL and letter knowledge were only marginally correlated ( $r = .23$ ) at Time 1. Additionally, de Jong and colleagues (2000) reported only a moderate relationship ( $r = .34$ ) between PAL and letter knowledge. Together, these findings do not lend support to a close relationship between letter knowledge and PAL.

Another relationship of interest was that of PAL and RAN. It has been hypothesized that RAN reflects the underlying ability to learn arbitrary visual-verbal associations (Manis et al., 1999). If this were the case, we would expect RAN to demonstrate a strong relationship with PAL (because PAL presumably taps visual-verbal learning more directly). However, in the present data, PAL and RAN were unrelated at both time points. These results are consistent with other studies demonstrating only weak to moderate correlations between PAL and RAN (Lervåg et al., 2009; Mayringer & Wimmer, 2000; Poulsen et al., 2012; Warmington & Hulme, 2012).

A final issue of particular interest for this thesis was the relationship between PAL and measures of memory for phonological forms, both short-term (i.e. digit span, nonword repetition) and long-term (i.e. expressive vocabulary). In line with the findings of Windfuhr and Snowling (2001), and our own conclusions from Chapter 2 and 3, PAL was unrelated to measures of verbal short term memory (although see de Jong et al., 2000). This indicates that successful learning of novel words in a PAL task

is not strongly dependent on verbal short term memory. Instead, PAL exhibited a significant concurrent relationship with expressive vocabulary at both time points. These findings are consistent with the suggestion put forth in Chapter 3 that PAL indexes the establishment of long-term phonological representations. Although de Jong and colleagues (2000) and Windfuhr and Snowling (2001) did not report a strong relationship between vocabulary and PAL, the vocabulary measures employed in these studies (receptive vocabulary and word definitions, respectively) differed crucially from ours in that we measured expressive vocabulary. Arguably, if PAL indexes phonological form learning, we would expect a stronger relationship with vocabulary measures that index knowledge of phonological forms, than vocabulary measures that primarily index semantic knowledge.

Interestingly, although none of the cognitive measures predicted unique variance in PAL at Time 1 in our regression analyses, vocabulary was the only concurrent measure to predict unique variance in PAL at Time 2. The fact that vocabulary was uniquely related to PAL at Time 2 (even when accounting for the concurrent relationship between phonological awareness and PAL) is consistent with the idea that PAL is not simply a measure of phonological awareness. Indeed, this is reflected in the consistent finding that, when measured concurrently, PAL reliably explains unique variance in reading even after accounting for phonological awareness (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001).

Although our results show that phonological awareness certainly influences PAL performance, PAL differs from phonological awareness in important ways. For example, whereas phonological awareness tasks require explicit access to, and manipulation of, stored phonological representations, PAL requires *learning* of novel phonological forms. The learning and establishment of stable phonological

representations may be crucially involved in spoken word learning, as suggested by the correlation between PAL and expressive vocabulary. We will return to the theoretical implications of the relationship between PAL and vocabulary in the General Discussion of this thesis.

Having summarized the findings, we are now in a position to consider the different theoretical models of the PAL-reading relationship set out in Figure 4.1. Our results are clearly incompatible with the causal model (Panel A), and the reciprocal model (Panel C), as PAL did not exert a longitudinal influence on reading. Instead, our findings are consistent with both the “third factor” model (Panel D) and the reverse causality model (Panel B).

In support of the “third factor” model, our data showed that whereas PAL did not predict reading longitudinally, the two measures were concurrently related at Time 2. This correlation may have been underpinned by phonological awareness, which exerted a longitudinal influence on both reading and PAL at Time 2. Evidence in support of the causal influence of phonological awareness on PAL comes from a training study by de Jong and colleagues (2000), in which training phonemic awareness in kindergartners led to improvements in visual-verbal PAL performance. As highlighted by the authors, an increasing awareness of the phonemic structure of language may enable more accurate encoding of phonological forms (see also, Snowling, Goulandris, Bowlby, & Howell, 1986; Windfuhr & Snowling, 2001). The influence of phonological awareness on novel word learning need not be constrained to encoding, however. Evidence shows that the quality of support available from long-term memory influences children’s ability to maintain and recall novel phonological forms in short-term memory (Hulme et al., 1991; 1995). Thus, children who come to the PAL task with well-specified phonological representations will likely be better able

to form accurate and stable phonological representations of the novel words within the task. Although phonological awareness is clearly implicated in PAL performance, our results are also compatible with a model of the PAL-reading relationship in which learning to read leads to growth in PAL performance, as shown in Figure 4.1, Panel B. Support for the influence of learning to read on PAL comes from evidence for the changing relationship between PAL and phonological awareness before and after the start of literacy instruction. Caution should be taken in the interpretation of this result, as the difference between the correlations at Time 1 and Time 2 did not reach significance in a formal statistical test ( $p = .069$ ). Additionally, de Jong et al (2000) and Lervåg et al. (2009) did report significant correlations between PAL and measures of phonological awareness. Nevertheless, the observation that the relationship between PAL and phonological awareness emerged only after the onset of reading instruction provides some indication that the skills indexed by PAL may change as a function of learning to read. Or at least that the relative importance of cognitive abilities, such as phonological awareness, may differ before and after the onset of reading instruction. Of course, the theoretical models outlined above are not mutually exclusive. For example, learning to read might bring about an increase in phonological awareness, particularly at the phonemic level, which in turn may serve to support the learning of novel words in PAL tasks.

One way in which learning to read may influence both PAL and phonological processing is through the acquisition of orthographic knowledge. Orthographic knowledge is known to influence performance on a range of phonological tasks that do not explicitly require written language (e.g., phoneme deletion, nonword repetition, auditory lexical decision) (Ehri and Wilce, 1980; Nation & Hulme, 2011; Seidenberg & Tanenhaus, 1979; Ziegler & Ferrand, 1998). For example, auditory lexical decisions

are faster for words with more orthographic neighbors, and are slowed down for words with inconsistent mappings from orthography to phonology; crucially, these effects are only found in individuals who are literate (Ventura, Morais, & Kolinsky, 2007; Ziegler, Muneaux, & Grainger, 2003; Ziegler & Muneaux, 2007). There are two primary theories to explain these findings. First, orthographic effects on spoken language processing may reflect automatic or strategic activation of orthographic representations (Kolinsky, 1998; Pattamadilok, Kolinsky, Ventura, Radeau, & Morais, 2007; Seidenberg & Tanenhaus, 1979). Alternatively, learning to read may fundamentally change, or restructure, phonological representations via the incorporation of orthographic information (Muneaux & Ziegler, 2004; Perre & Ziegler, 2008; Ziegler et al., 2003). On this view, learning orthographic representations of words actually drives the specification and segmentation of phonological representations themselves, such that words with more consistent mappings from orthography to phonology become better specified (Muneaux & Ziegler, 2004).

Regardless of the theoretical perspective one takes, it is clear that learning to read may influence performance on PAL tasks via newfound support from phonology and orthography. Children who are better readers would likely benefit from greater support, leading to better learning of the novel words in PAL tasks. Thus, rather than it playing a direct causal role in reading development, PAL (when measured in children who are literate) may be a proxy of the reading system itself. This provides a ready explanation for the robust PAL-reading relationship reported in children who are literate (see Chapter 2; Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001), despite evidence that PAL does not predict reading longitudinally when measured in pre-readers in our data and in Lervåg et al. (2009).

Of course the extent to which phonological and orthographic representations influence PAL performance is difficult to discern, given the highly interactive and reciprocal nature of phonology and orthography once children begin to read (e.g., Blaiklock, 2004; Hulme, Snowling, Caravolas, & Carroll, 2005; Muter et al., 2004; Perfetti et al., 1987). Although the lack of a longitudinal relationship between letter knowledge at Time 1 and PAL at Time 2 may seem to speak against a direct influence of orthographic knowledge on PAL performance, the regression weight was in the direction consistent with this notion, and letter knowledge and PAL demonstrated a moderate relationship at Time 1. Additionally, letter knowledge may have indirect effects on PAL through phonological awareness (and vice versa). Thus, although the present data are unable to adjudicate between the theoretical relationships shown in Panels B and D, they are clear in showing that rather than cause reading development, PAL is influenced by cognitive abilities that are closely linked to learning to read.

#### *A Final Note*

These conclusions rest on the assumption that our tasks are adequate measures of the cognitive abilities we wish to tap. In the case of PAL, our tasks showed acceptable reliability (as indexed by Cronbach's alpha) at both Time 1 ( $\alpha = .83$ ) and Time 2 ( $\alpha = .84$ ). These values are consistent with those reported by Lervåg and colleagues (2009) ( $\alpha$  ranging from .83-.85). However, it is worth considering whether Cronbach's alpha is the best index of reliability when it comes to PAL. Cronbach's alpha reflects the internal reliability of a measure; however, as PAL is a learning task that uses the same set of items across trials, alpha (on trials) is expected to be high. Thus, Cronbach's alpha may not be an optimal measure of reliability in the case of

PAL. Instead assessing the consistency of PAL across different tasks (i.e., parallel forms) would likely be a better approach.

In the course of evaluating the results, several observations led us to question the reliability of PAL in young children. First, PAL at Time 1 was only moderately correlated with PAL at Time 2 ( $r = .29$ ). Although we argued that this may reflect the changing nature of PAL as children learn to read, it may also reflect poor reliability. The longitudinal correlation indexes both the stability and reliability of PAL, and thus we cannot separate the contribution of these two factors to the observed correlation.

Another concern arose from the regression analyses in which we predicted PAL performance at each time point from a range of cognitive predictors (i.e., verbal short term memory, phonological awareness, expressive vocabulary, RAN, letter knowledge) hypothesized to be closely related to PAL. Together, these cognitive predictors were only able to account for a maximum of 14% of the variance in PAL at either time point. It is of course possible that we did not index the cognitive abilities that are in fact predictive of PAL performance; for example, we did not include a measure of nonverbal intelligence. However, the equivocal evidence for a relationship between nonverbal intelligence and PAL suggests it is moderate at best (de Jong et al., 2000; Mayringer & Wimmer, 2000; Warmington & Hulme, 2000). Additionally, even after taking variations in nonverbal intelligence (and age<sup>11</sup>) into account (accounting for approximately 14% of the variance in PAL), both Windfuhr and Snowling (2001) and de Jong et al. (2000) only accounted for a maximum of 22% of the additional variance in PAL using a similar battery of cognitive predictors to the current study. Given the theoretical motivation behind the selection of these cognitive measures, we were particularly surprised to find that even when PAL did exhibit a relationship with other

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<sup>11</sup> In contrast to the present study that examined PAL in the same year group (5-6 year olds), these studies tested PAL across a range of ages: Windfuhr & Snowling (2001), 7-11 years; de Jong et al (2000), 4.5-6.8 years

measures in our study (e.g., vocabulary, letter knowledge, phonological awareness, reading), these relationships were uniformly moderate ( $r$  never exceeding .29).

Potentially, the strength of the relationships observed between PAL and other cognitive predictors may be compromised (or limited) by poor reliability.

While we think it is important to highlight concerns regarding reliability, it is also important to note that we do not believe these issues undermine the general conclusions stemming from this chapter. Although we should take caution when interpreting the extent of the relationship between PAL and other cognitive abilities, the fact that we replicated the results of Lervåg and colleagues (2009), who used a technique much more robust to reliability issues (i.e. latent variable modeling) gives us confidence in the interpretation of our results regarding PAL. Reliability is clearly an important issue, however, and therefore will be discussed in more detail in the General Discussion.

## **Chapter 5: General Discussion**

*The research presented in this thesis addressed the nature, specificity, and causality of the PAL-reading relationship. In Chapters 2 and 3 we investigated the task demands that give rise to this relationship in both typically developing readers and children with dyslexia. In Chapter 4 we addressed the causal direction of this relationship by examining the development of PAL and reading ability from pre-literacy to the end of kindergarten. In this chapter, we present an overview of our main findings, followed by a discussion of the theoretical implications of these findings, and finally, a reflection on the limitations and future directions of research in this area.*

## Overview of Main Findings

*Elucidating the PAL-reading relationship*

There were two major aims of Chapters 2 and 3: first, to distinguish between the crossmodal and verbal accounts of the PAL-reading relationship, and second, to determine if this relationship holds across readers of different abilities. To address these aims, we employed a factorial design comprised of four PAL mapping conditions (i.e. visual-verbal, verbal-verbal, visual-visual, verbal-visual) that allowed for the dissociation of crossmodal and verbal task demands. We predicted that if the task component responsible for the PAL-reading relationship lies at the level of the association, any PAL task requiring a crossmodal association (i.e., visual-verbal, verbal-visual) should demonstrate a relationship with reading ability. In contrast, if the verbal response component is responsible for the relationship with reading, any task requiring verbal response learning (i.e., visual-verbal, verbal-verbal) should show a relationship with reading ability.

The results of Experiment 2.1 in typically developing readers were consistent with the predictions of the verbal account. Only tasks requiring verbal output (visual-verbal, verbal-verbal PAL) correlated with reading ability. Crucially, there was no evidence in favor of the crossmodal hypothesis; verbal-visual PAL, a task sharing crossmodal associative demand with visual-verbal PAL, was unrelated to reading. This provided evidence against a strong version of the crossmodal hypothesis. However, in light of Hulme and colleagues' (2007) finding that visual-verbal PAL explains variance in reading above and beyond verbal-verbal and visual-visual PAL, it remained possible that visual-verbal PAL shares a unique, direction-dependent relationship with reading ability.

To test this possibility, we examined whether the verbal-output component common to both visual-verbal and verbal-verbal PAL could account for the relationship with reading ability, or whether visual-verbal PAL enjoys a unique relationship with reading beyond the verbal-output component. The results of a latent variable model indicated that a “verbal-output PAL” factor explained variance in reading accuracy beyond that explained by phonological awareness and RAN (see Figure 2.2.). This model paralleled those observed separately for visual-verbal and verbal-verbal PAL (see Figure 2.1), and was consistent with the results of Warmington and Hulme (2012) for visual-verbal PAL. The fact that this pattern of findings held for the latent construct strongly indicates that the PAL-reading relationship stems from verbal-output demand. Moreover, the finding that visual-verbal PAL could not explain additional variance in reading beyond the latent verbal-output factor supports this conclusion.

#### *The locus of PAL deficits in dyslexia*

Moving now to the findings in children with dyslexia, the results of Experiments 3.1 and 3.2 revealed that children with dyslexia exhibit robust deficits in visual-verbal and verbal-verbal PAL (verbal-output conditions), but not visual-visual PAL or verbal-visual PAL. This pattern of findings is strikingly similar to the pattern in typically developing children, and further supports verbal-output as the task component responsible for the PAL-reading relationship.

However, given the phonological deficits widely associated with dyslexia, poor performance in visual-verbal and verbal-verbal PAL might be an expected consequence of the phonological demands of the task. Indeed the prediction of the verbal account is that these demands are responsible for PAL deficits in dyslexia. Although the lack of deficits in verbal-visual PAL clearly indicates that children with dyslexia do not

experience difficulties with crossmodal associative learning, it is important to determine whether PAL deficits can be reduced to difficulties with the phonological demands of the task, or whether these deficits are in fact specific to PAL. That is, poor performance in verbal-output PAL tasks could result from difficulty learning the verbal response item, difficulty forming associations with verbal response items, or additive effects from difficulties at both levels. Isolating these components of learning is especially important because visual-verbal PAL paradigms typically require verbal learning and associative learning to occur simultaneously<sup>12</sup>. In Experiment 3.3, participants learned a set of novel words in a verbal pre-exposure phase on Day 1, before learning to associate the novel words with symbols in the visual-verbal PAL phase on Day 2. By tracking learning on Day 1, we were able to determine the extent to which difficulty learning novel phonological forms could account for the visual-verbal PAL deficits observed in dyslexia. Unsurprisingly, children with dyslexia performed significantly below the level of age-matched controls in both the verbal learning and associative learning phases of the task. Crucially, however, deficits in visual-verbal PAL on Day 2 were fully explained by deficits in verbal learning on Day 1. Moreover, this relationship held at the item-level: the degree to which children learned a given novel word during the verbal learning stage predicted how well they learned to associate this word with a symbol in the visual-verbal PAL task. In other words, there was no evidence to support a view of additive or independent associative learning deficits in dyslexia. Indeed, children with dyslexia performed as well as controls on a receptive version of the PAL task (with the same paired associates for which they had shown robust deficits in the expressive PAL task). This provided further evidence that PAL

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<sup>12</sup> Here we should note that one approach to addressing this confound would be to use words rather than nonwords, as this largely eliminates the verbal learning component. However, this approach is problematic in that there may be pre-existing differences in children's knowledge, experience, or quality of phonological representations of the words.

deficits reflect difficulties linked exclusively to verbal, rather than associative, task demands.

Together, the results of Chapters 2 and 3 allowed us to address the extent to which verbal and crossmodal task demands determine the PAL-reading relationship. Importantly, by applying this design across experiments with typically developing children and children with dyslexia, we were able to speak to the conflicting theories emerging from these separate literatures on PAL. The results consistently showed that the PAL-reading relationship is specific only to verbal-output PAL tasks. Furthermore, the nature of this relationship appeared to be continuous, holding across reading abilities. Not only were the characteristics of the relationship the same regardless of whether we examined typically developing children or children with dyslexia, but the extent to which verbal learning predicted visual-verbal learning in Experiment 3.3 fully explained visual-verbal PAL performance regardless of group membership (i.e., dyslexic, control). In other words, including group membership in the model did not result in better model fit than a model in which group was not specified.

The continuity of the PAL-reading relationship across groups highlights the importance of considering typical reading and dyslexia as part of a continuum when formulating cognitive theories of reading development. If one takes a view of dyslexia as the lower tail of the normal distribution (e.g., Kovas et al., 2007; Shaywitz et al., 1992), it follows that the same underlying processes implicated in typical reading development should be important for reading in children with dyslexia. Thus a guide to understanding and assessing the multitude of deficits associated with dyslexia may be to start by asking: is this skill implicated in reading more generally?

*On the causal role of PAL in reading development*

The results of Chapters 2 and 3 clarified the specificity of the PAL-reading relationship. However, they also led to questions regarding the nature and direction of this relationship. In particular, the finding that phonological task demands are crucial for the emergence of the PAL-reading relationship suggests that, rather than playing a causal role in reading development, PAL may correlate with reading due to a common reliance on the phonological system. The results of Chapters 2 and 3 could not address the causal nature of the PAL-reading relationship because PAL and reading were measured concurrently. To begin to tease apart the relationship between PAL and reading development, we employed a longitudinal approach in Chapter 4.

The primary aim of the chapter was to distinguish between causal and purely correlational accounts of the PAL-reading relationship. We were specifically interested in testing whether the concurrent finding that PAL explains variance in reading ability above and beyond phonological awareness and RAN (Warmington & Hulme, 2012; Chapter 2 of this thesis) would replicate in a longitudinal model. The only previous study to examine the longitudinal contribution of PAL to reading did not find an effect of PAL (measured in pre-readers) on later reading ability in children learning to read Norwegian (Lervåg et al., 2009). It was important to test a longitudinal model in English, however, as it has been suggested that PAL may be particularly important in less transparent orthographies (Hulme et al., 2007; Lervåg et al., 2009).

In Experiment 4.1 we assessed a range of cognitive measures in children at the beginning of kindergarten (Time 1) before formal reading instruction began, and again at the end of kindergarten (Time 2). To address the longitudinal nature of the PAL-reading relationship, we constructed a model with PAL, letter knowledge, phonological awareness, and RAN at Time 1 as predictors of PAL and reading at Time 2. By

including PAL at both time points, we were able to examine whether PAL and reading are reciprocally related, or if the direction of the relationship runs in the reverse direction, with learning to read influencing growth in PAL.

The resulting model showed that whereas phonological awareness and letter knowledge at Time 1 predicted reading at Time 2, PAL did not explain unique variance in reading ability longitudinally. Yet, at Time 2, PAL demonstrated the expected concurrent correlation with reading. This suggests that the PAL-reading relationship is a consequence of learning to read, rather than a reflection of a causal influence of PAL on reading. Further support for this conclusion came from the finding that the relationship between PAL and phonological awareness changed over the first year of kindergarten. At Time 1, the two measures were unrelated, whereas they demonstrated a moderate correlation at Time 2. Additionally, although PAL and phonological awareness were unrelated at Time 1, phonological awareness exerted an independent influence on PAL at Time 2, beyond the autoregressive effect of PAL at Time 1. We argued that this changing relationship between PAL and phonological awareness may reflect the influence of learning to read, as this was the primary factor that changed from Time 1 to Time 2. On this view, learning to read may lead to greater awareness of the phonemic structure of language, which in turn, reciprocally influences reading development. This changing awareness of, and reliance on, phonological processing may lead to qualitatively different ways of performing the PAL task in pre-literate vs. literate children.

## Theoretical Implications

### *Reliability*

Before discussing the theoretical implications of our findings, it is important to consider factors that may influence the interpretation of our results discussed above. One important issue emerging from Chapter 4 concerns the reliability of PAL. In Experiment 4.1, the longitudinal correlation between visual-verbal PAL at Time 1 and Time 2 was only .29. As noted in the discussion of that chapter, this moderate correlation was difficult to interpret, as it may reflect poor reliability or a lack of stability over time. If, as we argued, learning to read changes the way in which children perform PAL tasks, we would not expect a strong correlation between PAL at the beginning and end of kindergarten. However, even if PAL were highly stable over time, we would not expect to find a strong correlation if the reliability of the task itself is limited. These issues cannot be separated by examining the longitudinal correlation alone, because it is indicative of both the stability and reliability of PAL over time.

We did not initially have concerns regarding the reliability of PAL, as it showed adequate reliability across our experiments as measured by Cronbach's alpha, summarised in Table 5.1 below. Furthermore, these values were consistent with those reported by Lervåg and colleagues (2009) ( $\alpha$  ranging from .83-.85) in pre-readers, Elbro, Daugaard, & Gellert (2012) ( $\alpha$  ranging from .90-.94), and Warmington and Hulme (2012) ( $\alpha = .84$ ), in literate samples.

Table 5.1

*Cronbach's alpha for PAL tasks across experiments*

	Experiment				
	2.1	3.1	3.2	3.3	4.1
Visual-Verbal	0.88	0.80	0.81	.81 <sup>a</sup> , .89 <sup>b</sup>	.83 <sup>c</sup> , .84 <sup>d</sup>
Verbal-Verbal	0.87	0.81	0.86		
Visual-Visual	0.79	0.82	0.80		
Verbal-Visual	0.80	0.72	0.76		

*Notes* .<sup>a</sup> Verbal learning phase; <sup>b</sup> Visual-verbal learning phase; <sup>c</sup> Time 1; <sup>d</sup> Time 2

Although Cronbach's alpha is high across studies, it is worth considering the utility of this measure in assessing the reliability of PAL. Cronbach's alpha is certainly useful in assessing the internal reliability of a measure; however, as PAL is a learning task that uses the same set of items across trials, alpha (on trials) is expected to be high. In fact, as highlighted by Poulsen et al. (2012), a PAL task can really be viewed as consisting of only one item (a fixed set of stimuli that repeats across trials), thus Cronbach's alpha may not be an appropriate metric of reliability. Although one could choose to calculate alpha on the individual items in the PAL task rather than trials, this too is problematic. PAL tasks for young children typically consist of only three items; Cronbach's alpha increases as a function of the number of items, thus it is expected to be small for such a limited item set size (Schmitt, 1996). Clearly, the utility of Cronbach's alpha is limited in the case of PAL.

So what is a more appropriate index of reliability? Ideally, reliability would be measured by examining the correlation of multiple PAL tasks using different items (i.e. parallel-forms). Indeed, this was the approach taken by Lervåg and colleagues (2009),

in which the authors administered three different versions of a visual-verbal PAL task, which were then used as indicators for a latent variable in pre-schoolers. However, across the studies presented in this thesis, we had only one measure of PAL at each measurement occasion<sup>13</sup>, making it difficult to resolve the issue of reliability in the experiments reported in this thesis. Likewise, to our knowledge, multiple indices of PAL have not been reported for any studies examining PAL in literate samples. This is cause for concern, as the majority of the positive findings on PAL have come from literate samples.

Among studies utilizing parallel PAL measures in pre-readers, the correlations between these measures have been similarly moderate, indicating that limited reliability is not just an issue for the tasks used in this thesis. For example, the concurrent correlations between parallel visual-verbal PAL tasks in the study by Lervåg and colleagues ranged from .28 to .57 (A. Lervåg, personal communication, May 1, 2013). Likewise, a concurrent correlation between PAL tasks of .40 was recently observed at the University of Copenhagen (M. Poulsen, personal communication, July 9, 2012). Furthermore, Byrne and colleagues (2012) used a standardized measure of sound-symbol learning from the Wide Range Assessment of Memory and Learning (WRAML; Adams & Sheslow, 1990) with preschool children, and found that performance in monozygotic twins correlated only .30; this suggests a need for improved reliability, despite the fact that Cronbach's alpha for the standardized measure (.88) gave no indication of poor reliability. Together, these results suggest that at least part of the explanation for the modest correlation between PAL at Time 1 and Time 2 in Experiment 4.1 might be limited reliability.

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<sup>13</sup>Although we had four measures of PAL in Experiments 2.1-3.2, examining the correlations between the mapping conditions would not have been a useful index of reliability because of the differences in mapping demand

Limitations in the reliability of PAL may have important implications for the conclusions drawn from the studies reported in this thesis and in the literature. Mainly, the relationship between PAL and other measures may be biased if the reliability of PAL tasks is poor. Whether these correlations are underestimated or overestimated depends on the correlations between their true scores, the extent of measurement error inherent in the measures, and the degree to which these measurement errors are correlated (Nimon, Zientek, & Henson, 2012). Regardless, limited reliability may account for the relatively weak correlations between PAL and other cognitive abilities observed in Experiment 4.1. Thus we must exercise caution when evaluating the strength of the relationships observed between PAL and other cognitive measures.

Notwithstanding this, we do not believe that the overall implications or interpretation of our results are likely to be compromised by the issues highlighted above. First, our major results concerning the PAL-reading relationship reported in Chapters 2 and 3 replicated previous findings in the literature. Additionally, in Chapter 2 we modelled the concurrent PAL-reading relationship using latent variables, thus accounting for measurement error in PAL and our other measures. In Chapter 3, we replicated the major findings in the literature concerning PAL deficits in dyslexia, while also replicating our own novel results across Experiments 3.1 and 3.2. And finally, in Chapter 4 our longitudinal model replicated critical aspects of Lervåg et al.'s (2009) study, in which the authors used latent variable modelling, and thus had a more robust index of PAL. The fact that the general findings reported in this thesis are consistent across experiments, and with findings discussed in the literature, indicates that we can interpret them with confidence. We now turn to consider the theoretical implications of our findings and in doing so, identify questions for future research.

*Crossmodal learning vs. verbal learning*

Despite the longstanding interest in the role of crossmodal mechanisms in learning to read, our results are clear in showing that variations in the ability to form crossmodal associations are largely unrelated to typical and atypical reading development. This conclusion comes from the results of Experiment 4.1, in which visual-verbal PAL failed to demonstrate a longitudinal relationship with reading and the finding from Chapters 2 and 3 in which verbal, rather than crossmodal mapping, demand accounted for the PAL-reading relationship.

That is not to say that crossmodal associative learning, particularly of grapheme-phoneme correspondences, is not important to reading. Indeed, knowledge of letter-sound correspondences is a crucial basis upon which decoding abilities are built (e.g., Byrne, 1998; Byrne & Fielding-Barnsley, 1989). A child unable to learn these associations would clearly fail to learn to read. However, our data suggest that individual differences in this ability, at least as tapped by PAL tasks, cannot account for variations in reading ability. Thus, although PAL may be a requirement of learning to read, it does not appear to be causally related to individual differences in reading development.

Of course, because all children who become literate eventually master letter-sound correspondences, it is possible that the influence of PAL is only apparent very early in development. That is, although the speed with which children acquire grapheme-phoneme correspondences will differ, this parameter may have little effect beyond allowing for the initial set-up of the reading system. For example, PAL might explain variations in the rate at which children acquire letter knowledge. Indeed, this was the motivation behind examining PAL in pre-readers in Experiment 4.1. However, as noted in Chapter 4, we were only able to assess the relationship between PAL and

letter knowledge at Time 1, as letter knowledge was at ceiling by the end of kindergarten. This precluded an analysis of the cognitive predictors of growth in letter knowledge. Potentially, the picture would look different if PAL were measured in an earlier developmental window. Yet, in a study by de Jong and colleagues (2000), and our own results from Chapter 4, the concurrent relationship between PAL and letter knowledge was only moderate. Additionally, the relationship between letter knowledge and PAL disappears once phonological awareness is taken into account (de Jong et al., 2000), suggesting that rather than reflecting associative learning, the relationship between letter knowledge and PAL may stem from the shared phonological processes. This suggestion fits nicely with the longitudinal model reported in Experiment 4.1 in which phonological awareness predicted growth in PAL. It also supports our general conclusion that, in contrast to its acronym, PAL appears to be much more heavily influenced by individual differences in verbal learning ability than associative learning ability.

The importance of verbal learning to the PAL-reading relationship is supported across the experiments reported in this thesis. Regardless of reading status (i.e., dyslexic, non-dyslexic), the ability to learn novel words in Experiment 3.3 fully explained variations in visual-verbal PAL performance. Furthermore, the analyses of errors in Experiments 3.2 and 3.3 supported a phonological locus of PAL deficits in dyslexia: children with dyslexia committed a higher proportion of phonological errors than controls in both visual-verbal and verbal-verbal PAL, while making a similar proportion of associative errors, a pattern consistent with the literature (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003). Additional analyses showed that when phonological errors were committed, children with dyslexia tended to make errors that were further from the target (i.e. differing by a greater number of phonemic features)

than those of controls. Thus, both the magnitude and severity of phonological errors tended to be greater in the dyslexic group. Together, these findings indicate that children with dyslexia experience substantial difficulty learning novel words.

It is important here to discuss why children with dyslexia might have difficulties learning novel phonological forms. Although phonological encoding is necessary for the formation of an initial phonological representation in short term memory, our data suggest that the difficulties experienced by children with dyslexia stem from later processes involved in learning, such as the maintenance and retrieval of the phonological representations. Across the experiments reported in Chapter 3, children with dyslexia did not exhibit difficulties with immediate short term memory for novel words that they subsequently struggled to learn. Furthermore, in the longitudinal study presented in Chapter 4, verbal short term memory (i.e., nonword repetition, digit span) was unrelated to PAL in pre-readers, a finding that held following a year of formal literacy instruction. In contrast, PAL demonstrated a concurrent relationship with expressive vocabulary both before and after the onset of literacy instruction, providing support for the conclusion that PAL taps longer-term phonological memory processes important for the establishment of phonological representations. Thus, although verbal short-term memory has been conceptualized as a language learning device (e.g., Gathercole & Baddeley, 1990) it does not seem to be a strong determinant of phonological form learning as indexed by our PAL tasks. Of course, by using CVC nonwords, our PAL tasks did not significantly stress verbal short term memory. A different pattern may have emerged had we used more complex, phonologically demanding stimuli, although it is important to note that even with the relatively simple stimuli used here, children showed substantial variation in the ability to learn novel words.

Although the initial encoding and immediate repetition of the novel words was accurate, our analyses strongly indicate that children with dyslexia experience difficulty building stable phonological representations. Across experiments and verbal-output conditions, children with dyslexia did not commit a higher proportion of perseverative errors (i.e. repeated errors) than controls, indicating that the majority of their errors constituted new errors. This shows that poor performance was not simply a case of learning inaccurate representations; instead, their difficulties were suggestive of deficits in the acquisition of stable and accurate phonological representations. This conclusion is supported by Mayringer and Wimmer (2000), who showed that providing a phonological cue (e.g. the first syllable in a nonword) at recall did not reduce the extent of visual-verbal PAL deficits in children with dyslexia. This indicates that the phonological representations had not been learned sufficiently for the cue to aid retrieval.

Before continuing, it is important to note that although our results clearly implicate the “verbal-output” component of PAL tasks in driving the relationship with reading ability, our data do not allow us to determine if the processes tapped by verbal-output PAL are specific to the acquisition of phonological-output representations, or the ability to learn novel phonological representations more generally (regardless of input or output<sup>14</sup>).

The fact that verbal-visual PAL was unimpaired in dyslexia and unrelated to reading ability in typically developing readers certainly suggests that phonological-output processes are crucial to the PAL-reading relationship. This is a tempting conclusion, especially given the implication of phonological-output deficits in reading disability (e.g., Hulme & Snowling, 1992; Nation et al., 2001; Ramus & Szenkovits,

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<sup>14</sup> The extent to which phonological input and output representations are dissociable is a theoretical issue beyond the scope of this thesis (see Martin & Saffran, 2002 for an overview).

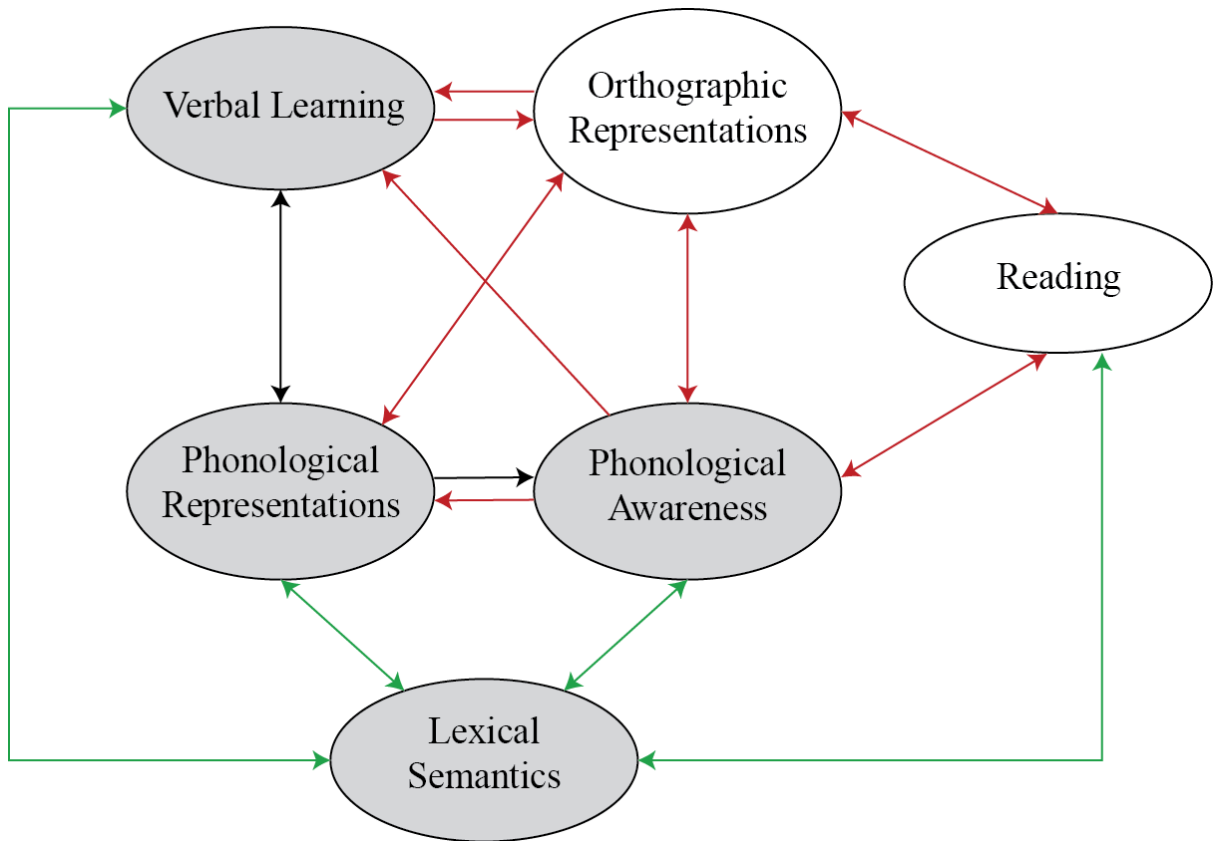
2008; Snowling & Hulme, 1994; Swan & Goswami, 1997; Truman & Hennessey, 2006). However, it is possible that verbal-visual PAL lacked the sensitivity to detect individual differences in the establishment of a novel phonological representation because verbal-input PAL tasks only require the recognition of phonological forms. Whereas children could presumably perform well on a verbal-visual PAL task without having formed precise phonological representations of the novel words (e.g. by relying on partial cues), this is not the case on a verbal-output PAL task, as successful performance depends on explicit recall and output of a fully-specified phonological representation. An experiment in which the demands of a verbal-visual PAL task were increased to require fully specified phonological representations (e.g., by using nonwords differing by only one phoneme) would allow for a more direct comparison of the importance of input and output phonology in explaining the PAL-reading relationship. Regardless of whether the verbal learning processes are specific to output representations, our data are clear in suggesting that the ability to acquire novel phonological representations represents the crucial source of variation in PAL.

#### *From phonological form learning to reading*

How might verbal learning relate to reading ability? There are at least three, non-mutually exclusive possibilities, displayed in Figure 5.1. A first possibility is that verbal learning exerts an indirect influence on reading via effects on phonological representations before children learn to read. On this view, verbal learning influences the establishment of long-term phonological representations, which in turn affects the development of phonological awareness, and ultimately, reading. This account is best understood within the framework of the lexical restructuring hypothesis (Fowler, 1991; Metsala, 1997; Metsala & Walley, 1998; Walley, 1993). According to this hypothesis,

children's phonological representations are initially holistic; as vocabulary grows, however, the substantial phonological overlap between words forces the system to reorganize and represent increasingly smaller segmental units (i.e., phonemes). Crucially, this hypothesis predicts that phoneme-level representations, and eventually explicit phoneme awareness, are consequences of growth in oral vocabulary. The role of verbal learning in this context, therefore, is in the set-up of the phonological system that goes on to support reading.

This "pre-reading" system is depicted in grey in Figure 5.1. The influence of phonological form learning on phonological representations and phonological awareness is shown in the black arrows. As indicated by the bi-directional arrows, the relationship between verbal learning and phonological representations is reciprocal: the quality of existing phonological representations stems from initial verbal learning, but the ability to learn novel phonological forms is highly dependent on the quality of support from existing phonological representations (Hulme et al., 1991; Hulme et al., 1995). Although our experiments focused on phonological form learning, vocabulary acquisition clearly involves learning novel phonological forms and the semantic representations attached to those forms. The influence of lexical semantics on verbal learning and phonological representations is an extremely important aspect of the system, although not an aspect to which our data can speak; for this reason we have depicted this component of the system in green.



*Figure 5.1.* Visual schematic of the potential direct, indirect, and reciprocal relationships between verbal learning and reading. Single-headed arrows indicate direct influences, and double-headed arrows indicate bi-directional influences. Grey ovals represent the pre-reading oral language system: black arrows represent phonological influences on the pre-reading system, green arrows represent semantic influences. White ovals depict the addition to the system when children learn to read: red arrows represent the influence of learning to read on the language system.

Although the lexical restructuring account specifies a role for verbal learning in the development of the phonological system before the onset of reading, learning to read will lead to reciprocal influences on the phonological system, as shown by the red arrows in Figure 5.1. A second account of the relationship between verbal learning and reading, therefore, is that it reflects (at least in part) the integrity of the reading system itself. On this view, children who are better readers would have higher quality phonological and orthographic representations available to support verbal learning. In its most basic form, learning to read introduces orthographic representations to the language system, while also leading to further development of phonological awareness. This would no doubt lead to increased support for verbal learning via direct influences from phonology and orthography. The influence of learning to read on verbal learning is likely far more complex, however. As discussed in Chapter 4, orthographic representations may have profound effects on phonological representations themselves (e.g., Muneaux & Ziegler, 2004; Ventura et al., 2007; Ziegler & Ferrand, 1998; Ziegler & Muneaux, 2007). According to this account, as children learn to read, orthographic representations “contaminate” phonological representations, such that they become incorporated into the phonological representations themselves (Muneaux & Ziegler, 2004). This can be seen as an extension of the lexical restructuring hypothesis, whereby words with more consistent mappings from orthography to phonology become better specified (i.e., undergo more lexical restructuring) than those with inconsistent mappings. The influence of learning to read on the language system will not only improve verbal learning ability via increased support, it may also fundamentally alter the language system in such a way that children approach verbal learning in a qualitatively different way before and after the onset of literacy.

A final possibility, outlined in the discussion of Chapters 2 and 3, is that as children learn to read, phonological form learning plays a direct role in the acquisition of orthographic knowledge (Elbro et al., 2012; Mayringer & Wimmer, 2000; Tunmer & Chapman, 2012). When children encounter words in their written form for the first time, they are faced with the task of decoding the word to arrive at its pronunciation and meaning. To some extent, the product of this decoding attempt will always deviate from the spoken pronunciation (e.g., the blended form “duh-o-guh” is not the same as “dog”), although the distance will increase as a function of the irregularity of the spelling (e.g. *yacht* will deviate more than *dog*). Either way, the orthographically-derived *spelling pronunciation* will be a novel phonological form. This form must be utilized during reading to arrive at the correct spoken pronunciation of a word (Elbro et al., 2012; Tunmer & Chapman, 2012). Evidence suggests that through repeated experience, these *spelling pronunciations* become lexicalized, and activated in parallel with the spoken representations during reading (Ranbom & Connine, 2011). Individual differences in the ability to learn novel phonological forms would clearly lead to variations in learning spelling pronunciations. If these pronunciations support the acquisition of word-specific orthographic knowledge, children with deficits in verbal learning might be expected to have corresponding deficits in orthographic knowledge (Mayringer & Wimmer, 2000). The direct influence of verbal learning on orthographic representations is shown by the red arrow in Figure 5.1.

Having set out the possibilities, we will now consider the results of our experiments in the context of these theoretical relationships between verbal learning and reading ability. The longitudinal study presented in Chapter 4 suggested that PAL is influenced by learning to read, with phonological awareness predicting growth in PAL over the first year of kindergarten. We argued that this may reflect the increasing

awareness of the phonemic structure of language (in concert with the acquisition of orthographic representations), which is available to support PAL performance once children learn to read. These findings are clearly in line with the view that learning to read has a powerful influence on verbal learning ability. In contrast, the results of the longitudinal model were not consistent with a direct effect of verbal learning on orthographic representations, as PAL did not exert a longitudinal influence on reading development. It is important to remember, however, that although verbal-output PAL tasks may rely crucially on verbal learning, our tasks were not designed to test verbal learning ability, or the theories outlined above. Thus, even though our results do not support a direct influence of verbal learning on reading development, this does not speak strongly against the theory itself. Finally, our data do not allow for a direct test of the hypothesis that verbal learning influences reading indirectly via lexical restructuring. One way to do this would be to test verbal learning at a younger age and then examine both direct effects on the development of phonological awareness before the onset of reading, and indirect effects (via phonological awareness) on later reading development.

Although our data cannot speak directly to this theory, it is consistent with a range of findings in the dyslexia literature. Carroll and Snowling (2004) demonstrated that children at family-risk for dyslexia (ranging in age from 3;11-6;06 years) were impaired in verbal learning, as indexed by a task in which children learned names for pictures in the context of a storybook. Phonological form learning deficits accompanied a range of deficits in phonological processing, particularly those involving expressive (output) phonology. This is clearly in line with the verbal-output PAL deficits reported in Chapter 3 of this thesis. Interestingly, Carroll and Snowling found that children with expressive phonology (i.e., speech) impairments, in the absence of non-phonological

language problems, incurred a similar level of risk for reading difficulties as the children at family-risk for dyslexia (see Bird, Bishop, & Freeman, 1995, for a comprehensive discussion of the relation between speech deficits and reading disability). The authors argued that both groups are on a continuum of risk for reading failure that stems from aberrant development of the phonological system. Specifically, they suggested that deficits in phonological form learning impede the development of phonemically-segmented phonological representations, leading to poor performance on any task requiring access to well-specified representations, and ultimately, a difficulty utilizing these representations in learning to read. Although some of the children in this study were at the very beginning stages of reading, selecting children based on prospective risk for reading difficulty indicated that verbal learning deficits may precede reading failure.

As discussed above, deficits in phonological form learning are expected to have consequences for the quality of phonological representations that become stored in long-term memory. Consistent with this, children with dyslexia are generally thought to have phonological representations that are underspecified or indistinct (e.g., Elbro, 1996; Elbro, 1998; Fowler, 1991; Snowling, Wagtendonk, & Stafford, 1988). Yet, poor phonological form learning is often observed on experimental tasks in spite of age-appropriate performance on measures of crystallized vocabulary (Carroll & Snowling, 2004; Wimmer et al., 1998; Chapter 3 of this thesis). This finding highlights the importance of considering the difference between phonological form knowledge and semantic knowledge when discussing vocabulary. Vocabulary acquisition clearly involves both semantic and phonological form learning, processes that are, in part, dissociable (Duyck et al., 2003; Freeman & Martin, 2001). Children with dyslexia (without co-morbid language difficulties) generally do not exhibit deficits in semantic

learning of novel objects, even when they have failed to learn the phonological forms associated with these objects (e.g., Aguiar & Brady, 1991; Vellutino et al., 1995). Consistent with this pattern, children with dyslexia typically perform as well as their age-matched peers on receptive vocabulary tasks, or vocabulary measures tapping semantic knowledge (e.g., definitions), but exhibit robust deficits in tasks tapping phonological form knowledge (i.e., expressive naming/expressive vocabulary) (e.g., Katz, 1986; Nation et al., 2001; Snowling et al., 1988; Swan & Goswami, 1997; Wolf & Obregon, 1992 ). Thus, although children with verbal learning deficits may show age-appropriate performance on vocabulary measures primarily tapping semantic components of vocabulary, it seems likely that deficits would emerge on expressive vocabulary tasks designed to assess knowledge of phonological forms.

The literature discussed above provides support for the theory that phonological form learning is important for the establishment of long-term phonological representations. Although our experiments were not designed to test this theory, we believe it holds much promise as an explanation for the relationship between verbal learning ability and learning to read. It is recommended that future research examine the nature of this relationship through the use of longitudinal designs commencing early in language development, both with large-scale unselected samples and children at-risk for dyslexia. Such designs would provide a clearer picture of the temporal relationships between phonological form learning, vocabulary development, and phonological awareness in the pre-reading system, before the powerful effects of learning to read complicate measures of verbal learning.

## Connections to theories of word learning

*Complementary Learning Systems*

In understanding the verbal learning processes tapped by verbal-output PAL tasks, and how these processes may relate to long-term phonological representations, it is useful to consider theoretical models of word learning. According to a complementary learning systems account of lexical learning, the acquisition of a new word involves two separate, but highly interactive memory systems (e.g., McClelland, McNaughton, & O'Reilly, 1995; Norman & O'Reilly, 2003; O'Reilly & Norman, 2002; O'Reilly & Rudy, 2001). The hippocampal system supports rapid "episodic" learning of novel phonological forms, and is especially sensitive to specific features of stimuli; in contrast, the neocortical system supports long-term retention of words through a more gradual process that abstracts away from specific learning episodes and integrates representations according to statistical regularities (Davis & Gaskell, 2009; Norman & O'Reilly, 2003; O'Reilly & Rudy, 2001). Through repeated experiences with novel words, stable cortical representations are formed and integrated with existing representations in a process referred to as *lexicalization*; importantly, although phonological form learning can occur quite rapidly, the establishment of new lexical entries in long-term memory occurs over a longer time course, and may require periods of off-line consolidation (i.e., sleep) (Dumay & Gaskell, 2007; Gaskell & Dumay, 2003; Henderson, Weighall, Brown, & Gaskell, 2012; McClelland et al., 1995).

The framework outlined above is useful in conceptualizing the learning processes involved in the acquisition of novel words in verbal-output PAL tasks. This learning is best understood as the rapid hippocampal learning involved in the initial acquisition of novel phonological forms. Recent experiments conducted within the

experimental framework described above indicate that in individuals with dyslexia, novel phonological forms do not become integrated with existing lexical representations (demonstrated by lexical competition effects) following the same exposure and time course as that shown for typically developing readers (Warmington, Dumay, Gaskell, Snowling, & Hulme, in prep). Warmington and colleagues (in prep) suggested that novel phonological representations may be too underspecified to support these consolidation processes. Together with evidence for abnormal off-line consolidation processes in dyslexia (e.g., Bruni et al., 2009; Mercier, Pivik, & Busby, 1993), these findings provide more direct support for the relationship between phonological form learning and the establishment of long-term phonological representations in memory. Future work would benefit from combining the methodological approach described above with that taken in the developmental literature. Mainly, it is important to utilize methods that allow for a more direct examination of how novel phonological representations become integrated within the existing phonological system, and how the acquisition of novel representations influences lexical restructuring. But it is also crucial to investigate these processes in pre-literate children, before the influence of learning to read complicates the inferences that can be drawn from studies examining verbal learning. A longitudinal design following pre-readers with and without family-risk for dyslexia would elucidate the temporal relationships between verbal learning, lexical restructuring, phonological awareness, and literacy outcome.

### *Hebb Learning*

A final theoretical account of word learning that is relevant to the verbal learning deficits observed in this thesis comes from the literature on Hebb learning. The Hebb effect (Hebb, 1961) refers to the gradual improvement of immediate serial recall

for a sequence of items that repeats across trials, in comparison to unchanged immediate serial recall performance for non-repeating sequences. This effect appears to reflect (largely implicit) long-term learning of serial-order information, which has been argued to be a naturalistic analogue of word learning. For example, Szmalec, Duyck, Vandierendonck, Barbera-Mata and Page (2009) demonstrated that through repeated exposure to sequences of phonemes (e.g., la-va-bu), stable long-term representations in which the sequences are represented as a lexical unit (e.g., *lavabu*) can be formed. Recently, Szmalec, Loncke, Page, and Duyck (2011) presented evidence showing deficient Hebb learning in adults with dyslexia across auditory, visual-verbal (e.g. syllables presented visually in an orthographic form), and visuospatial conditions. The authors argued that dyslexia is characterized by a domain-general serial-order learning deficit, in which poor learning of sequential information leads to impoverished long-term memory for both spoken (phonological) and written (orthographic) forms.

Clearly, the learning aspect of this hypothesis is consistent with our interpretation of verbal learning deficits observed in our PAL tasks. However, our account differs from the Hebb account in two crucial respects. First, the Hebb learning deficit proposed by Szmalec and colleagues is proposed to be domain-general, whereas our data are inconsistent with this view. Instead, our findings are indicative of a domain-specific *verbal learning deficit*, as deficits occurred selectively in verbal-output, but not visual-output PAL conditions. Second, although we would subscribe to a view in which the learning deficits in dyslexia are linked to a failure to learn optimally through repeated exposure, the Hebb account specifically implicates serial-order learning. We were unable to evaluate serial learning deficits in our visual-output conditions, as each visual stimulus consisted of one symbol that could not be broken down into constituent parts/serial position. However, the error analyses for the verbal-

output conditions were not consistent with difficulties specific to serial learning. If a primary deficit in serial order learning were at work in our experiments, we would expect to find substantial inversion errors (e.g., “mib” → “bim”) in our error analyses. However, this was an extremely rare occurrence: inversion errors comprised less than 1% of errors in visual-verbal and verbal-verbal PAL in Experiment 3.2 and did not occur with any frequency in Experiment 3.3. Of course, monosyllabic CVC words do not place significant stress on serial order processing and it could be that more inversion errors would emerge if more complex stimuli were used. Nevertheless, children with dyslexia demonstrated significant difficulty learning the novel words across experiments, despite the lack of any evidence for errors that were serial in nature.

*Concluding comments: limitations and future directions*

Limitations of the experiments presented in this thesis have been discussed throughout, but before concluding, it is worth highlighting some important points. First, indications from our own findings and those reported in the literature on PAL are indicative of poor task reliability. It is recommended that future research examine the reliability of PAL more closely, and take a latent variable approach to investigating the relationship between PAL and other cognitive measures. Second, our results are limited in the extent to which they can speak to orthographic learning deficits in dyslexia, as our visual stimuli comprised single symbols. The use of multi-symbol orthographic stimuli would better address this issue, while also allowing for a test of domain-general learning deficits (as predicted by the Hebb learning account). Finally, although we can say that a verbal-output component drives the PAL-reading relationship, we cannot conclude with certainty that this applies only to the learning of novel phonological forms, because this component was inherent in the PAL tasks utilized in this thesis. As

mentioned throughout this thesis, utilizing PAL tasks with words is a problematic approach to addressing this issue, in that individual differences in learning may reflect pre-existing differences in knowledge of the word forms. A better approach might be to train participants to criterion with novel words, and then examine if performance on a PAL task with these novel words correlates with reading ability.

Our discussion of the theoretical implications of the data presented in this thesis led to the hypothesis that verbal learning plays an indirect role in reading development via effects on the establishment of long-term phonological representations and the development of phonological awareness. In the course of our discussion, we highlighted key questions that need to be addressed by future work. We will briefly outline the methodological approaches recommended to test this hypothesis. To start, longitudinal studies following children from early childhood through to the development of skilled reading would allow for an investigation of how verbal learning influences the pre-reading phonological system, and in turn, how this system influences the development of the reading system. Ideally, verbal learning would be assessed in the developmental window in which children experience rapid growth in vocabulary development. In determining if verbal learning deficits early in development represent a risk factor for dyslexia, it will also be important to include at-risk samples (i.e., family risk of dyslexia, children with speech deficits, and children with language impairments). Finally, in addition to examining the longitudinal relationship between verbal learning, phonological processes, and reading ability, it is strongly recommended that future work design experiments that allow for more direct investigations of these relationships. For example, the behavioral and neurophysiological approaches utilized within the complementary learning systems account would nicely complement the longitudinal approaches outlined above.

To conclude, the experiments presented in this thesis demonstrated that despite the longstanding interest in the role of crossmodal mechanisms in learning to read, variations in the ability to form crossmodal associations are largely unrelated to reading development. In contrast, the findings provided overwhelming support for the importance of phonological form learning (in tasks requiring output) in explaining the PAL-reading relationship. Future research is needed to elucidate the relationship between verbal learning and reading development.

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## Appendices

### Appendix A

*Stimulus-response pairs by mapping condition (see notes for experiment specific information)*

#### Visual-Verbal PAL

	Stimulus Item	Response Item
1		Vek
2		Nal
3		Yut
4		Mib
5		Jof
6		Zeep

*Notes.* The full set for each mapping condition was used in Experiment 2.1 and 3.1. In Experiment 3.2, the stimulus-response pairs were as follows: visual-verbal (1, 3, 4, 5), verbal-verbal PAL (1, 2, 3, 5), visual-visual (1, 3, 4, 5, 6), verbal-visual PAL (2, 3, 4, 5, 6). Experiment 3.3: visual-verbal PAL (1, 2, 3, 4, 5). Experiment 4.1: visual-verbal PAL, Time 1 (pairs 1 and 3 from original visual-verbal PAL set, and pair 5 from the original verbal-visual PAL set), visual-verbal PAL, Time 2 (4, 5, 6 from the original visual-verbal PAL set).







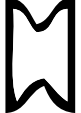





## Verbal-Verbal PAL

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	Stimulus Item	Response Item
1	Pel	Von
2	Hib	Kag
3	Tus	Joad
4	Lom	Mef
5	Reat	Fup
6	Nad	Yiz







---

Visual-Visual PAL

	Stimulus Item	Response Item
1		
2		
3		
4		
5		
6		

## Verbal-Visual PAL

---

	Stimulus Item	Response Item
1	Sut	
2	Yibe	
3	Kav	
4	Zon	
5	Fim	
6	Tep	

---

## Appendix B

*Fixed effects on PAL performance in Experiment 3.1*

	Estimate	SE	Wald-Z	p
Intercept	-1.41	0.13	-10.54	< .001
Modality	-0.24	0.22	-1.07	.283
Output	1.59	0.21	7.56	< .001
Dyslexic	-0.48	0.22	-2.14	.030
Block	0.26	0.04	6.32	< .001
Modality x Output	-0.11	0.36	-0.30	.767
Modality x Dyslexic	0.25	0.33	0.75	.453
Output x Dyslexic	0.83	0.29	2.83	.005
Modality x Block	-0.11	0.07	-1.68	.092
Output x Block	-0.03	0.07	-0.34	.732
Dyslexic x Block	-0.12	0.08	-1.53	.127
Modality x Output x Dyslexic	-0.03	0.40	-0.06	.950
Modality x Output x Block	-0.02	0.13	-0.13	.895
Modality x Dyslexic x Block	0.05	0.13	0.39	.696
Output x Dyslexic x Block	0.09	0.14	0.62	.537
Modality x Output x Dyslexic x Block	-0.01	0.26	-0.05	.959

*Fixed effects on PAL performance Experiment 3.2*

	Estimate	SE	Wald-Z	p
Intercept	-0.14	0.17	-0.83	.409
Modality	-0.13	0.27	-0.48	.635
Output	0.96	0.29	3.33	< .001
Dyslexic	-0.38	0.24	-1.59	.113
Block	0.36	0.04	8.30	< .001
Modality x Output	-0.12	0.53	-0.23	.822
Modality x Dyslexic	0.01	0.24	0.06	.954
Output x Dyslexic	0.82	0.30	2.76	.006
Modality x Block	0.11	0.08	1.27	.205
Output x Block	0.01	0.09	0.15	.884
Dyslexic x Block	-0.24	0.07	-3.59	< .001
Modality x Output x Dyslexic	0.17	0.41	0.42	.672
Modality x Output x Block	-0.22	0.17	-1.26	.206
Modality x Dyslexic x Block	0.13	0.13	1.05	.292
Output x Dyslexic x Block	0.02	0.14	0.14	.889
Modality x Output x Dyslexic x Block	0.17	0.25	0.67	.502

*Fixed effects on verbal learning and visual-verbal PAL in Experiment 3.3*

		Estimate	SE	Wald-Z	p
Verbal Learning	Intercept	-0.23	0.22	-1.04	.297
	Group	-1.2	0.37	-3.21	.001
	Block	0.41	0.09	4.47	< .001
	Group x Block	-0.02	0.18	-0.12	.906
Visual-Verbal PAL	Intercept	0.05	0.2	0.26	.793
	Group	-0.9	0.39	-2.29	.022
	Block	0.26	0.07	3.74	< .001
	Group x Block	0.01	0.14	0.05	.960
t-value					
Item-specific prediction of Visual-Verbal PAL from Verbal Learning	Intercept	2.54	0.19	13.38	< .001
	Verbal Learning	0.42	0.11	3.93	< .001
	Group	-0.54	0.38	-1.43	.153
	Verbal Learning x Group	0.12	0.22	0.58	.562