Paired associate learning deficits in poor readers: the contribution of phonological input and output processes

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Paired associate learning deficits in poor readers: the contribution of phonological input and output processes

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Abstract

It is well-established that poor readers exhibit deficits in paired associate learning (PAL), and there is increasing evidence for a phonological locus of these deficits. However, it remains unclear whether poor performance stems from difficulties specific to the phonological output system, or difficulties that affect both phonological input and output processes. Understanding these deficits is important not only in the context of PAL, but also for informing broader theories of typical and atypical reading development. We developed a novel paradigm that allowed us to assess PAL in the presence and absence of phonological output demands. Fourteen poor readers and fourteen age-matched controls were first trained to criterion in verbal-visual PAL before being tested in the visual-verbal direction. The results showed that poor readers learned at the same rate as controls in verbal-visual PAL, even when the nonword stimuli were phonologically confusable. Yet despite having reached the same criterion as controls in verbal-visual PAL, poor readers exhibited robust impairments for those same paired associates in visual-verbal PAL. The overall pattern of results is most consistent with the conclusion that PAL deficits reflect impairments to the phonological output system; however, results that may challenge this interpretation are also discussed.

Keywords: Paired associate learning; poor readers; phonological deficit; phonological output; dyslexia

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The ability to learn orthography-phonology mappings is crucial to reading development. In the first instance, learning to read requires the acquisition of letter-sound associations. To the novice reader, these associations are arbitrary. It is the discovery of the systematic nature of these associations, however, and the understanding that they represent speech sounds, that allows children to begin to decode written words (e.g., Byrne, 1998; Liberman, Shankweiler, Fischer, & Carter, 1974). The ability to utilise and form new connections between orthography and phonology may also play an important role in later stages of reading development. According to Ehri and colleagues (Ehri & Saltmarsh, 1995; Ehri, 2005), sight word acquisition depends crucially on having automatic access to both sublexical and lexical orthography-phonology mappings. The most common method employed to probe the dynamic associative learning thought to be involved in acquiring orthography-phonology mappings is paired associate learning (PAL). In a PAL task, participants learn to pair a stimulus item and a response item in memory, such that the presentation of the stimulus elicits the response.

A substantial body of work has demonstrated a relationship between PAL and reading ability. In typically developing children, visual-verbal PAL (i.e., mapping a symbol onto a spoken word or nonword) and verbal-verbal PAL (i.e., associating spoken words or nonwords) are strongly correlated with reading accuracy and fluency (Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Litt, van Bergen, de Jong, & Nation, 2013; Warmington & Hulme, 2012; Windfuhr &Snowling, 2001). Furthermore, visual-verbal and verbal-verbal PAL explain unique variance in reading ability, even after accounting for robust predictors such as phonological awareness and rapid automatised naming (RAN; Litt et al., 2013; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). This suggests that PAL may tap cognitive abilities that are independent from known predictors of reading development. The

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evidence also suggests that general associative learning ability is not responsible for the PAL-reading relationship because visual-visual PAL (i.e., associating pictures or symbols) is unrelated to reading ability (Hulme et al., 2007; Litt et al., 2013). Instead, cognitive skills such as cross-modal associative learning (Hulme et al., 2007; Windfuhr & Snowling, 2001) and phonological learning (Litt et al., 2013; Litt & Nation, 2014; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2006; Nielsen & Juul, 2015) have been proposed to drive this relationship.

The pattern of relationships in typically developing children is mirrored in the dyslexia literature. Children with dyslexia show robust impairments in visual-verbal PAL (e.g., Mayringer & Wimmer, 2000; Messbaer & de Jong, 2003; Li, Shu, McBride-Chang, Liu, & Xue, 2009; Litt & Nation, 2014; Vellutino, Scanlon, & Spearing, 1995; Vellutino, Steger, Harding, & Phillips, 1975) and verbal-verbal PAL (Litt & Nation, 2014; Zigmond, 1966). These deficits cannot be explained by impaired associative learning or the processes involved in mapping a visual stimulus onto an oral response because children with dyslexia do not exhibit deficits in visual-visual PAL (Li et al., 2009; Litt et al., 2013; Messbauer & de Jong, 2003; Vellutino, Steger, & Pruzek, 1973) or visual-auditory PAL (i.e., learning associations between symbols and sequences of oral sounds such as humming, coughing, puckering lips) (Vellutino et al., 1975; Torgesen & Murphey, 1979). Together, the findings from typically developing readers and children with dyslexia tell a strikingly similar story: the PAL-reading relationship emerges only when there is a verbal component to the associations to be learned; nonverbal associative learning is unrelated to reading ability. The current study focuses on isolating the cognitive skills tapped by verbal PAL tasks to determine the locus of the deficit in poor readers.

In attempting to understand why verbal PAL tasks are related to reading ability, it is essential to highlight several findings from the literature. First, the importance of the verbal

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component is closely tied to the phonological properties of the stimuli. For example, even when poor readers show robust impairments in learning the names of novel symbols or objects, they are able to learn and utilise knowledge about those same paired associates in comprehension tasks (Aguiar & Brady, 1991; Kalashnikova & Burnham, 2016; Litt & Nation, 2014). This indicates that children with reading difficulties are not impaired in learning the semantic properties of the verbal stimuli. In line with this, Vellutino and colleagues (1995) showed that children with dyslexia are not impaired in visual-verbal PAL if non-phonological routes to learning are available (e.g., learning words that are high in meaning vs. words that are low in meaning) (Vellutino & Scanlon, 1985; Vellutino et al., 1995). This fits nicely with the observation that the extent to which deficits emerge in verbal PAL tasks is a function of the phonological and semantic characteristics of the stimuli: deficits are largest for nonwords, moderate for abstract or low frequency words, and small or non-existent for concrete or high frequency words (Elbro & Jensen, 2005; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2006; Vellutino et al., 1995).

Direct evidence for the role of phonological skills in verbal PAL tasks comes from a training study by de Jong, Seveke, and van Veen (2000). The authors showed that training in phonological awareness and letter-sound knowledge improved visual-verbal PAL in pre-readers, whereas training in semantic categorization had no effect. Additional evidence comes from a study by Litt and Nation (2014), in which children learned novel spoken nonwords in a free recall task one day prior to a visual-verbal PAL task using those same nonwords. Children with dyslexia were poorer than controls in both the free recall task and visual-verbal PAL; but crucially, the deficit in visual-verbal PAL was fully explained by the preceding deficit in nonword learning. Mayringer and Wimmer (2000) 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. The authors argued that

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children with dyslexia had not learned the phonological representations sufficiently for the cue to aid retrieval, and that their difficulty was thus in learning rather than retrieving phonological representations. Together, these findings suggest that visual-verbal PAL is predicated on how efficiently and accurately phonological representations have been established in memory, but they are limited in that they only test phonological learning within the context of a phonological output task.

If phonological learning is key to explaining the PAL-reading relationship, one would expect any PAL task requiring novel word learning to correlate with reading. Yet recent results reported by Litt and colleagues (Litt et al., 2013; Litt & Nation, 2014) do not support this prediction. In a series of studies, the authors administered four PAL mapping tasks to typically developing children and children with dyslexia: visual-verbal, verbal-verbal, visual-visual, and verbal-visual (associating spoken nonwords with symbols). As predicted, both visual-verbal and verbal-verbal PAL shared a strong relationship with reading ability, and children with dyslexia were impaired in both tasks. However, verbal-visual PAL was both unrelated to reading ability in typically developing children, and unimpaired in dyslexia. These findings contradict the theory that the PAL-reading relationship is driven by phonological learning, because all three of the verbal PAL tasks involved learning novel words. The key difference between verbal-visual, visual-verbal, and visual-verbal PAL is that the former only involves input phonology, whereas the latter tasks involve both input and output phonology. This dissociation between performance on phonological input PAL tasks and phonological output PAL tasks raises questions as to the nature of the phonological impairments tapped by verbal PAL tasks.

There are two theoretical accounts of these findings. First, the phonological deficit indexed by PAL may in fact be output-specific. Some researchers have postulated that dyslexia is marked by deficient phonological output processes, despite unimpaired

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phonological input processes (Catts, 1989; Griffiths & Snowling, 2001; Hulme & Snowling, 1992; Ramus & Szenkovits, 2008; Shankweiler & Crain, 1986; Snowling & Hulme, 2004; Truman & Hennessey, 2006). Phonological output processes encompass the online access, retrieval, planning, and articulation of phonological representations stored in memory. The common thread amongst theories is that impairments arise only under task demands that require phonological output processes, though there is disagreement regarding which of these specific processes is responsible for deficits in dyslexia. Extending this view to PAL, the asymmetry between phonological output tasks (i.e., visual-verbal, verbal-verbal) and phonological input tasks (i.e., verbal-visual) may be explained by deficits that are situated within the phonological output system. If deficits are specific to phonological output, we would not expect children with dyslexia to exhibit poor learning in verbal-visual PAL because this task does not involve phonological output processes.

Alternatively, PAL deficits may result from impairments to the phonological system that affect learning regardless of whether it occurs via phonological input or output. The assumption of many theories of phonological deficits in dyslexia is that poor learning results in the storage of phonological representations in long-term memory that are fundamentally impoverished, degraded, or underspecified (e.g., Elbro & Jensen, 2005; Fowler, 1991; Fowlert, Swainson, & Scarborough, 2004). If dyslexia is marked by aberrant acquisition of phonological representations, this should be apparent in both phonological input and output PAL tasks. On this view, the apparent PAL task asymmetry is a consequence of differences in task sensitivity (i.e., visual-verbal PAL is more sensitive than verbal-visual PAL), rather than a reflection of output-specific phonological deficits. Thus PAL deficits should be discernible in verbal-visual PAL provided sufficient task sensitivity because phonological learning is inherent in the task.

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Task sensitivity is an issue that extends beyond PAL and deserves careful attention when interpreting patterns of normal and impaired performance in dyslexia (Ramus & Ahissar, 2012). Task sensitivity has been implicated in explaining the disproportionate evidence for phonological output versus input deficits on a range of tasks (Poulsen, 2011) and may readily explain the pattern of deficits observed in PAL. Consider that phonological output PAL tasks necessarily require one to explicitly recall and produce the nonwords with precision; anything less and the response will be scored as incorrect. In contrast, phonological input PAL tasks only require correct perception or recognition of the nonwords, making it much more difficult to detect individual differences in the precision with which they have been learned. Additionally, the extent to which children learn nonwords in a phonological input task is likely dependent on the characteristics of the stimuli (e.g., the degree to which each phonological feature of a nonword is needed to distinguish it from the other items in the set. In the verbal-visual PAL task employed by Litt and Nation (2014), it is possible that participants only learned the salient features of the nonwords (e.g., onset, rime) because the nonword stimuli were maximally distinct (i.e., no repetition of phonemes between words). This would have allowed for substantial variation in the quality of the phonological learning across participants, without necessarily resulting in variation in performance. In contrast, such variation in the quality of learning clearly would not have been tolerated in a verbal-output PAL task because participants must produce the nonwords. Therefore, it remains possible that verbal PAL tasks index a broad phonological learning deficit that is not restricted to phonological output.

If task sensitivity explains the lack of verbal-visual PAL deficits in dyslexia, it follows that deficits should emerge if the phonological input demands are increased to require precise encoding of each nonword. One way to increase phonological demands is to manipulate the confusability of the nonwords (i.e., the extent of phonological overlap). It has

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been proposed that phonologically confusable stimuli provide a strong index of representational quality by measuring the *distinctness* of phonological representations (e.g., Elbro, 1996; Messbauer & de Jong, 2006). If children with dyslexia acquire less distinct phonological representations than typically developing children, this should be most apparent in a learning task utilizing confusable nonwords because learning depends crucially on establishing precise representations.

The current study

To summarise, although there is strong evidence for a phonological locus of PAL deficits in dyslexia, it remains unclear whether poor performance stems from difficulties specific to phonological output. Understanding these deficits is important not only in the context of PAL, but also for informing the broader debate regarding the locus of phonological deficits in dyslexia (e.g., Elbro, 1996; Fowler, 1991; Hulme & Snowling, 1992; Ramus & Szenkovits, 2008;). Traditional measures of phonological abilities are limited in that they tap crystallized knowledge, often conflate phonological input and output processes, and can require complex meta-linguistic skills. PAL offers a dynamic measure of learning in which stimulus properties, exposure levels, and phonological input and output demand can be tightly controlled.

The current study aimed to determine whether PAL deficits reflect impairments specific to phonological output. We addressed this aim in two ways. First, we asked whether poor readers[1] exhibit PAL deficits in the absence of phonological output demand. To answer this question, we examined verbal-visual PAL under phonologically confusable (i.e., high degree of phonemic overlap between nonwords) and non-confusable conditions (see also Messbauer & de Jong, 2006). Following the results of Litt and Nation (2014), we did not

[1] Our sample was selected based solely on experimental criteria (defined in the Method section) and not based on a formal clinical diagnosis of dyslexia. Because experimental and clinical cut-offs can differ, we use the term *poor readers* throughout the paper to describe our sample of children with reading difficulties

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expect to find deficits in the non-confusable condition because precise phonological learning is not necessarily required for associative learning success. The key question was whether deficits would emerge in the confusable condition, in which successful associative learning depends more heavily on forming precise phonological representations of the overlapping nonwords. If so, this would support a pervasive phonological learning deficit that is not restricted to phonological output. Second, we asked whether phonological output demand induces poor PAL performance when prior learning has been tightly controlled in a phonological input PAL task. To answer this question, we employed a training procedure in which all participants were trained to the same criterion in verbal-visual PAL *before* testing in the visual-verbal (i.e., phonological output) direction. We predicted that if poor readers have output-specific phonological impairments, they should exhibit visual-verbal PAL deficits even though they were trained to the same criterion as controls in verbal-visual PAL.

Method

Participants

Sixty-four children aged 8 to13 years were recruited via Macquarie University research databases and flyers as part of a larger study. Children were invited to participate in the study based on: a) data indicating that they had average or poor reading ability (if recruited via database), or b) parent report of average or poor reading ability (if recruited via flyers). All participants spoke English as a first language, had normal or corrected-to-normal vision, and had no history of Attention Deficit/Hyperactivity Disorder (ADHD) or language delay.

Seventeen participants completed a pilot version of the PAL task that was used to determine the number of items for the final task. The remaining 49 children completed the final experimental PAL tasks. Two experimental groups were selected from these participants

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based on their scores on the reading measures (described below). We defined poor reading as pervasive difficulty affecting multiple reading subskills (i.e. lexical/sublexical, accuracy/fluency). Children were identified as poor readers if they scored more than one standard deviation below the mean on three or more of the five reading subtests. Fourteen children (6 female; 8 years, 4 months – to 12 years, 1 month) met this criterion[2]. We then selected a control group from the 33 remaining participants. Children needed to score between Z = -0.67 and 1.67 (i.e., 25-95th percentile) on all five reading subtests to meet criteria for the control group[3]. This was to ensure that reading performance was in the normal range and representative of typically developing readers. Ten children were excluded based on reading scores below this cut-off. The majority of these children had been recruited for the study based on prior data or parent report of poor reading ability, but had failed to meet the criteria for inclusion in the group of poor readers. A further nine children were excluded based on reading scores that were higher than the cut-off for inclusion in the control group. The final age-matched control group consisted of 14 typically developing readers (8 female; 8 years, 5 months-10 years, 11 months). Descriptive characteristics for both groups can be found in Table 1. As expected based on the selection criteria, the groups did not differ in age. The poor readers were impaired across all reading measures, with particularly poor performance on regular and nonword reading measures (>1.5 SD below the mean).

Materials and Procedure

Participants completed two 60-minute sessions, approximately one week apart. The sessions were individually administered by one of two trained researchers in a quiet testing

[2] Nine of the fourteen poor readers obtained Z-scores < -1 on four or more of the reading subtests.
[3] An exception was made for one participant who scored slightly above the cut-off for TOWRE Sight Word Efficiency (95th percentile) but within the acceptable range for all other reading measures. This was to keep group size equivalent and boost statistical power. All analyses were checked without this participant and the pattern of results remained the same.

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room at the university. In each session, children completed a series of cognitive measures and either the confusable or non-confusable PAL task. The cognitive measures were administered in the same order for all participants. The PAL tasks were counterbalanced across sessions to control for order effects.

Selection measures. The following reading measures were used to select participants.

Word reading fluency. Word reading fluency was measured with the Sight Word Efficiency subtest from the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999). In this task, children are instructed to read down a list of 104 words as quickly and accurately as possible. The raw score is defined as the total number of words that are read correctly in 45 seconds. Average alternate-form reliability across the age ranges for this measure is .91.

Nonword reading fluency. Nonword reading fluency was measured with the Phonemic Decoding Efficiency subtest from the TOWRE (Torgesen et al., 1999). In this task, children read down a list of 63 nonwords as quickly and accurately as possible. The raw score is defined as the total number of nonwords read correctly in 45 seconds. Average alternate-form reliability across the age ranges for this measure is .92.

Regular, irregular, and nonword reading. The Castles and Coltheart Reading Test-2 (CC2; Castles et al., 2009) was administered as a measure of regular, irregular, and nonword reading accuracy. Children read aloud 40 regular words (e.g., bed), 40 irregular words (e.g., cough), and 40 nonwords (e.g., pofe) of varying difficulty. The items are presented on flashcards with the regular, irregular, and nonword items intermixed in a list of 120 items. The order of the items is fixed and increases in difficulty as the test progresses. 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 all categories are discontinued, the stopping point is reached for each

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category, or all 40 words are read correctly in each category. The test yields separate scores for regular, irregular, and nonword reading. Reported Cronbach's alpha for these subtests is .85, .86, and .94, respectively (Moore, Porter, Kohnen, & Castles, 2012).

Cognitive Measures.

The following cognitive skills were measured to describe the cognitive profiles of both groups, but did not form part of the selection criteria. Descriptive characteristics of the groups are shown in Table 1. All participants scored at or above the expected range for nonverbal reasoning and processing speed, indicating that general cognitive skills were not impaired in either group. The groups did not differ significantly in RAN digits or phoneme deletion, but the poor readers performed significantly worse than the control group in nonword repetition and RAN letters. Although the lack of group differences in phoneme deletion was somewhat unexpected, it is worth noting that the group average on this task was at the tail-end of the normal range. The lack of group differences was likely driven in part by the control group performing slightly lower than the expected population mean. Additionally, poor readers showed impairments on other measures that rely heavily on phonological processes (i.e., nonword repetition, RAN, nonword reading).

Nonverbal reasoning. The Wechsler Abbreviated Scale of Intelligence (WASI) Matrix Reasoning (WASI; Wechsler, 1999) subtest provided an estimate of nonverbal reasoning ability. The test consists of 35 abstract spatial reasoning problems in which an array is presented with one missing section. Participants choose the item that belongs in the missing section from five options. Split-half reliability for this measures is .87.

Phoneme Deletion. Phoneme deletion was measured with the Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, Rashotte, & Pearson, 2013). In this test children are asked to delete single phonemes from words (e.g., "Say *bold* without the *b*"). Cronbach's alpha for this measure is .89.

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Nonword repetition. The Nonword Repetition subtest of the CTOPP (Wagner et al., 2013) was administered as a measure of phonological working memory. Participants hear a nonword and must immediately repeat it allowed. The 18 nonwords vary in length from one to six syllables, with the items increasing in length as the test progresses. Cronbach's alpha for this measure is .78.

Processing speed. The Coding subtest of the Wechsler Intelligence Scale for Children (WISC; Wechsler, 2003) was administered as an index of processing speed. In this task, children are presented with a key showing pairings between symbols and numbers (1-7). They are given 120 seconds to work through a grid of 90 numbers, using the key to draw the correct symbol below each number. Test-retest reliability for this measure is .85.

Rapid automatized naming (RAN). The Denckla and Rudel (1976) rapid naming of digits and letters was administered as a measure of rapid automatized naming of alphanumeric symbols. Five digits (6, 9, 4, 2, 7) or 5 letters (a, d, p, o, s) are presented in a 5 x 10 array, with each item appearing ten times in the array. Children name the items from left to right as quickly as possible until they have named all 50 items. Accuracy and total naming time (in seconds) are recorded. Data is excluded if children make more than three errors. No children were excluded from our data based on this criteria. Test-retest reliability for RAN digits and RAN letters is .80 and .72, respectively.

[INSERT TABLE 1]

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Experimental Tasks. The full experiment and corresponding scripts are available for download via the Open Science Framework: osf.io/y3rvk. The stimuli selection and characteristics are described below, followed by the task procedures. The tasks were presented on 15-inch Apple Macbook Pro laptops running Windows 7 SP1. The presentations were programmed using MATLAB R2011b (Mathworks Inc.) and Psychtoolbox 3.0.10 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). All visual stimuli were presented centrally on the screen.

The stimuli described below were used to create four paired-associates for the non-confusable PAL condition and four paired-associates for the confusable PAL condition. Based on pilot testing with children, four paired-associates was the optimal number of items in a PAL task needed to induce variance in trials to criterion without being too difficult for children to learn within a maximum of 20 trials.

Nonwords. Four non-confusable and four confusable nonwords were selected to create the two nonword sets (see Appendix A). In the non-confusable set, overlap in phoneme identity and positioning was minimised between the nonwords (i.e., *teb, mif, yut, vog*). In the confusable set, two potential phonemes were selected for each position (initial consonant, vowel, final consonant), such that each phoneme appeared in the same position twice in the set, and each nonword served as a minimal pair for another nonword in the set (i.e., *zek, vek, zib, vib*). To ensure that the nonwords in each set were high in name agreement (and thus reliably perceived across participants), pilot testing was conducted with four potential sets of nonwords in each condition. Ten adults listened to audio recordings of 32 phonotactically legal CVC nonwords (i.e., four non-confusable sets, four confusable sets). The nonwords were presented in a random order for every participant, with each nonword presented twice within the task, once in a male voice and once in a female voice with an Australian accent. After hearing a nonword, participants were asked to write down what they perceived. Name

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agreement was calculated by comparing participants' responses with the target response. Responses were scored as correct if there was full agreement between the phonemes represented in the written response and the phonemes in the target nonword (i.e., variations in orthographic form were accepted as long as the phonemes were correctly represented). The final nonword sets were matched for name agreement, $t(3) = -0.51$, $p = .63$, with the high levels of name agreement in the non-confusable (97.94%) and confusable (98.76%) sets. The two sets were also matched for phonological neighbourhood size, $t(3) = -0.55$, $p = .61$, (non-confusable, $M = 11.25$, $SD = 1.26$; confusable, $M = 12$, $SD = 2.45$).

Symbols. Twelve symbols were selected to create a pool of symbols to be paired with the nonwords (see Appendix A). The symbols came from a set of abstract symbols from extinct written languages that have been utilised in previous PAL studies with developmental samples (see Litt et al., 2013 for details of original selection criteria).

Paired Associates. The paired associates were created by randomly choosing eight of the symbols to pair with the nonword stimuli for each participant. This procedure meant that any given symbol could appear in either the non-confusable or confusable condition. This minimised visual or pair-specific effects on performance and maximised the likelihood of systematic effects arising from the phonological manipulation of interest. The nonword sets were fixed such that all participants were exposed to the same nonwords in the non-confusable PAL condition and in the confusable PAL condition. Participants were always exposed to the non-confusable and confusable sets in separate test sessions (counterbalanced order), administered approximately one week apart.

Tasks. All tasks described below were completed in a single test session for one PAL condition (i.e., non-confusable, confusable) and repeated again a week later for the other PAL condition. Thus the procedure for the non-confusable and confusable PAL conditions was identical. The experimental tasks were presented within a story about a robot preparing to

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travel to “Planet Zorb.” The child’s objective was to help the robot learn spoken words and their corresponding symbols from the alien language so they could blast off to planet Zorb and meet the aliens. The task was designed to keep participants engaged and motivated. Each phase of testing was designed to assess component cognitive processes necessary for successful PAL performance. An overview of the procedure for each phase is shown in Figure 1.

On each trial, a green ring appeared in the center of the screen and participants clicked it when they were ready for the trial to commence. We opted for individual trial initiation to control for differences in cognitive preparation which may differ as a function of reading ability (Badcock & Kidd, 2015). To encourage the formation of an abstract, rather than acoustic, representation of the nonwords, we presented the nonwords in a female voice on half the trials and a male voice on half the trials in all tasks (Ramus & Szenkovits, 2008). In the nonword repetition and exposure phase, participants heard the female voice in block one, followed by the male voice in block two. Participants were told that the voices would change but that the words would be the same. For all other tasks, the order of presentation of the female and male voice was randomised within each task.

Nonword Repetition and Exposure. This phase was designed to assess immediate phonological input/output processes for the nonwords before participants were exposed to the symbols or paired associates. Participants were instructed to listen to the nonwords and repeat each one aloud immediately after hearing it. If a participant did not repeat a nonword correctly, the experimenter provided feedback by saying, “That’s not quite right. The word is ‘X’ ”. The participant then repeated the nonword a second time. Following the nonword repetition block, participants engaged in two blocks of nonword exposure trials. The order of the nonwords in each block was randomised.

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Verbal-Visual PAL. In this phonological input PAL task, participants heard the nonwords and were asked to select the corresponding visually presented symbol[4].

Exposure Trials. Training began with two blocks of exposure trials to familiarise participants with the paired associates. In each block, participants saw four symbols presented horizontally across the computer screen. They were instructed to click on each of the symbols (in any order) to hear the associated nonwords. Participants were told to watch and listen carefully, as they could only click on each symbol once in each block. When a participant clicked on a symbol, a blue ring appeared around the symbol and the name of the symbol was presented in both the female and the male voice (order randomised) with a one second gap between presentations.

Learning to Criterion. Following exposure to the paired associates, participants engaged in the verbal-visual learning trials. On each trial, participants heard a nonword and saw the four symbols displayed horizontally across the screen. To ensure that selection was unaided by spatial memory, symbol order was random on each trial. Participants selected the symbol that they thought corresponded to that nonword and feedback was provided to promote learning. Selection accuracy was indicated by presenting a green (correct) or red (incorrect) ring around the symbol. The incorrect symbols were then removed (correct remained on screen) and the nonword was repeated. This procedure continued until all paired associates reached the criterion of two correct of the last three trials (for that item). After a paired associate reached criterion, it was not presented again during the task. This criterion

[4] As the focus of our study was on the phonological component of PAL, we chose to minimize the demands of the visual component of the experiment. Although requiring children to draw/write (i.e., output) the symbols would have more closely matched the output demands of visual-verbal PAL, there is no indication that this component causes difficulty for children with dyslexia. For example, children with dyslexia do not show verbal-visual or visual-visual deficits even when required to draw the symbols on every trial (Litt & Nation, 2014; Messbauer & de Jong, 2003; Vellutino et al., 1975). Given that there is no indication that this component is crucial to explaining PAL deficits in dyslexia, we chose not to include written production in verbal-visual PAL.

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was preferred to a mean performance criterion because it is sensitive to item-specific learning and ensures that participants learned each paired associate to the desired level.

Reinforcement Blocks. There were two reinforcement blocks that followed the same procedure as the exposure trials described above. The reinforcement trials were included to refresh participants' memory for all of the paired associates before the test phase. This was important because not all paired associates reached criterion at the same rate, so paired associates that were learned faster may have been subject to more forgetting than those that were learned more slowly.

Verbal-Visual Associative Knowledge. As a final measure of verbal-visual knowledge, participants completed two blocks of test trials without feedback. As in the verbal-visual learning trials, participants heard a nonword and saw all four symbols on the screen (the order in which the symbols appeared was random for each nonword). Participants were instructed to select the symbol that corresponded to the nonword.

Visual-Verbal PAL. This phase was designed to examine the effect of requiring phonological output on PAL performance. On each trial, a symbol appeared at the center of the screen and participants were asked to say the corresponding nonword. Each block consisted of four trials (one for each symbol) presented in random order. Feedback was not provided in the first two blocks, to provide an initial index of performance. Following this, participants engaged in up to five further blocks with feedback in which the correct answer was repeated after the response. If participants completed two consecutive blocks with 100% accuracy, testing was discontinued and full credit was given for the remaining trials.

Component Knowledge Tests. The component knowledge tests were designed to assess participants' knowledge of the symbols, nonwords, and associations in isolation to provide additional information regarding the source of any deficits observed in the PAL

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tasks. The receptive nature of these tasks also ensured that performance would not be affected by any phonological output difficulties. No feedback was provided on these tasks.

*Symbol Knowledge***.** Symbol knowledge was assessed with a yes/no recognition test. Each symbol was presented centrally with a green and red ring at the bottom of the screen. For each symbol, participants were asked to indicate whether it was a symbol they had learned. Participants clicked green for "yes," or red for "no." Half of the symbols were items learned in the PAL task, and half were close visual foils that differed from the target symbol by only one visual feature (see Appendix A). Items were presented randomly, with each target and each foil appearing twice in the task.

Nonword Knowledge. Knowledge of the nonwords was assessed with a yes/no recognition test. The procedure was identical to the symbol knowledge test except that the stimuli comprised aurally presented nonwords. Half of the nonwords were from the PAL task, and half were foils that differed from a target nonword by only one phoneme (see Appendix A). Items were presented randomly, with each target and each foil appearing twice in the task[5].

Visual-Verbal Associative Knowledge Test. Associative knowledge in the visual-verbal direction was measured using a four alternative forced choice (4AFC) task. Participants saw a symbol at the top of the screen and four icons of audio speakers across the bottom of the screen. They were instructed to click on each of the speakers (in any order) to hear the nonwords and then select the nonword that corresponded to that symbol. To minimise working memory load, participants were allowed to click on the speakers as many times as necessary before making their selection. There were two blocks of four trials: one per paired associate, presented in random order. All of the symbols and nonwords were items

[5] Piloting indicated that name agreement was high for the foils in the non-confusable (98%) and the confusable condition (98.29%), suggesting that despite the close phonological similarity with the target nonwords, they could be easily and accurately perceived.

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that had been learned in the PAL task (i.e., no foils). This procedure ensured that performance depended on associative knowledge, rather than item-specific knowledge. Additionally, administering the task in the visual-verbal direction kept the mapping direction consistent with the visual-verbal PAL task, but eliminated the need for verbal output.

[INSERT FIGURE 1]

Results

Model Specification

Verbal-visual and visual-verbal PAL were analysed using generalized linear mixed effects models constructed using the lme4 package (Bates, Maechler, Bolker, &Walker, 2015, version 1.1-9) in R version 3.2.2 (R Development Core Team, 2015). For details on model fitting procedures and specification, please see the supplementary materials. Before fitting the models, we examined the distribution of the data for each task. No outliers were identified and thus all available data were included in the analyses. We also examined whether age influenced PAL performance. There was no significant relationship between age and performance in either group, with the both strong and weak PAL scores spanning the age distribution. Therefore, we did not include age in our analyses. Finally, given the complexity of the experiment and the resulting multiple planned comparisons, we used the Benjamini-Hochberg procedure to control the false discovery rate (Benjamini & Hochberg, 1995; Benjamini, & Yekutieli, 2001). For all analyses, we report the raw *p* values, except in cases where the correction for multiple comparisons changed the interpretation of the results, in which case we also report the adjusted *p* values.

Below we first report the results pertaining to verbal-visual PAL to assess learning via phonological input, followed by visual-verbal PAL to assess phonological output, and finally, the measures of nonword, symbol, and associative knowledge.

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Nonword Repetition

Overall, nonword repetition was accurate in both children with reading difficulty (M= .90, SD =.12) and typically developing readers (M = .91, SD = .10). The few errors on the initial trials were self-corrected following feedback, indicating that the errors did not represent persistent difficulties with the perception or output of these nonwords.

Verbal-Visual Learning to Criterion

The average trials required to reach criterion in the confusable and non-confusable conditions is displayed in Figure 2. Overall, both groups required more trials to reach criterion in the confusable (controls: M = 4.38, SD = 2.24; poor readers: M = 5.57, SD = 3.10) than the non-confusable condition (controls: M = 3.77, SD = 1.39; poor readers: M = 3.98, SD = 1.55). To test whether poor readers required more trials than controls to reach criterion in verbal-visual PAL, we fitted a generalized linear mixed effects model (GLMM) in Lme4[6]. There was no difference between the groups in the number of trials to reach criterion for verbal-visual PAL, $b = 0.62$, $SE = 0.42$, $t = 1.49$, $p = .136$. More trials were needed in the confusable than the non-confusable condition, $b = -1.19$, $SE = 0.52$, $t = -2.30$, $p = .022$; and there was no interaction between group and condition, $b = -0.86$, $SE = 0.90$, $t = -0.96$, $p = .335$.

[INSERT FIGURE 2]

Verbal-Visual Associative Knowledge. The verbal-visual knowledge test assessed the knowledge of the paired associates directly following training to criterion. The proportion correct for each condition is shown in Table 2. A mixed effects logistic regression model was constructed using GLMM in Lme4. There was no difference in accuracy between groups, b =

[6] This package allows for data to be modelled according to non-linear distributions; our dependent variable, trials to criterion, represents the number of occurrences of an individual item until a success (in this case, meeting the criterion) was achieved. This data was not expected to follow a normal distribution, and indeed was best represented by a Gamma distribution. The superiority of this distribution over a Gaussian or Poisson distribution was confirmed by explicit comparison of model fit statistics (e.g., AIC, BIC) for equivalent models fit with each distribution, $\chi^2(1) = 107.35$, $p < .001$.

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-0.27, *SE* = 0.48, *Z* = -0.56, *p* = .574. Accuracy was higher in the non-confusable than the confusable condition, *b* = 2.07, *SE* = 0.53, *Z* = 3.92, *p* < .001. There was no interaction between group and condition, *b* = -1.26, *SE* = 0.99, *Z* = -1.27, *p* = .204. These results indicate that training to criterion was effective in ensuring that the groups did not differ in their knowledge of the paired associates prior to the start of visual-verbal PAL testing.

[INSERT TABLE 2]

Visual-Verbal PAL

We next addressed the question of whether accuracy in visual-verbal PAL differed between the groups following training to criterion in verbal-visual PAL. To answer this question, we constructed a mixed effects logistic regression model using GLMM in Lme4. Note that the results of our models were consistent regardless of whether we examined the two test blocks without feedback separately from the five blocks with feedback, or pooled the data across all seven blocks. For this reason, we report only the results of models combining all seven blocks of visual-verbal test trials below. Performance is summarised in Figure 3.

Visual-Verbal Test. Results of a mixed effects logistic regression model revealed significant main effects of condition, *b* = 1.23, *SE* = 0.48, *Z* = 2.57, *p* = .010, group, *b* = -2.77, *SE* = 0.61, *Z* = -4.56, *p* = <.001, and block, *b* = 0.31, *SE* = .04, *Z* = 8.67, *p* = <.001. These were qualified by an interaction between condition and block, *b* = 0.18, *SE* = 0.07, *Z* = 2.50, *p* = .012. Tests of simple main effects indicated that the interaction was driven by steeper (i.e., faster) learning in the non-confusable condition, *b* = 0.40, *SE* = 0.05, *Z* = 7.47, *p* <.001, relative to the confusable condition, *b* = 0.22, *SE* = 0.05, *Z* = 4.66, *p* <.001. There were no significant interactions between group and condition, *b* = -1.28, *SE* = 0.85, *Z* = -1.51, *p* = .131, or condition, group, and block, *b* = 0.04, *SE* = 0.14, *Z* = 0.26, *p* = .793. The interaction between group and block, *b* = -0.15, *SE* = 0.07, *Z* = -2.16, *p* = .031 did not survive the correction for multiple comparisons (adjusted *p* = .054). These results indicate that

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children with reading difficulty performed poorly in comparison to controls across all blocks of learning and in both the confusable and non-confusable conditions.

Although the above model describes performance on visual-verbal PAL, it does not take into account any differences in the rate at which initial learning occurred in verbal-visual PAL. Potentially, individual differences in the rate at which participants reached this criterion could explain significant variance in visual-verbal PAL (i.e., differences in learning rate may indicate subtle differences in quality of learning). If this were the case, we might expect the main effect of group to diminish once earlier learning is taken into account. To test this possibility, we first constructed a model predicting visual-verbal PAL from trials to criterion in verbal-visual PAL. Trials to criterion was a significant predictor of visual-verbal PAL, $b = -0.12$, $SE = 0.03$, $Z = -3.49$, $p < .001$. We next compared the model fit of this model to a model in which all main effects and interactions for our independent variables (i.e., group, condition, block) were added after accounting for trials to criterion. This provided a test of whether the effects reported in our original models remained after accounting for trials to criterion. This second model provided significantly better model fit, $\chi^2(9) = 209.63$, $p < .001$, with all of the main effects and interactions remaining significant and in the same direction as the original model reported above (for detailed results, see the supplementary materials). Finally, we also assessed whether the deficit in visual-verbal PAL remained after accounting for item-level performance on the verbal-visual associative knowledge test following verbal-visual training. Once again, the pattern and strength of the results were unchanged by accounting for earlier learning (details available in the supplementary materials). To summarise, although including trials to criterion significantly improved model fit, it did not change the overall pattern of the results; accounting for individual differences in verbal-visual learning rate did not explain the robust visual-verbal PAL deficits exhibited by poor readers.

[INSERT FIGURE 3]

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Analysis of Errors. The raw total errors in visual-verbal PAL indicated that poor readers made nearly twice as many errors (568) as controls (292). These errors were categorised into the following error types: "don't know" responses (poor readers=45, controls=37), associative errors (i.e. correctly pronounced nonword, incorrect pairing; poor readers=164, controls=157), and phonological errors (i.e. incorrectly pronounced nonword; poor readers =359, controls=98). It is apparent from these raw errors that poor readers made four times as many phonological errors as controls, whereas the total associative errors was similar in both groups.

To analyse these errors, we calculated the proportion of phonological and associative errors made by poor readers and controls (Table 3). Before doing so, we removed "don't know" responses from the total errors so that proportions reflected errors in which a child attempted a response. These error types were submitted to a log-linear model with fixed effects for group and condition and random effects by subject and item. Results showed that poor readers were more likely to make phonological errors than controls, $b = 1.45$, $SE = 0.40$, $Z = 3.63$, $p < .001$ in both the non-confusable and confusable conditions. Because error types are not independent (making one type of error automatically excludes the other type of error), this also means that poor readers were less likely than controls to make associative errors.

[INSERT TABLE 3]

Component Knowledge Tests

Symbol Knowledge. Performance on the yes/no recognition test for symbols (Table 2) was analysed by calculating and comparing d-prime (d') scores for each participant by PAL condition. Higher d' scores indicate better discriminability between targets and noise. The following formula was used to calculate d' scores: d'= z(hit rate)-z(false positive rate) after adjusting for extreme values using the log-linear approach (Hautus, 1995). The d' scores

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for the symbol recognition test were submitted to an ANOVA with condition (non-confusable, confusable) as a within-participants factor and group (poor readers, controls) as a between-participants factor. There was no significant difference in symbol knowledge between the groups, $F(1, 25) = 1.68$, $p = .206$, $\eta_p^2 = .06$. For both groups, d' scores were lower in the confusable than the non-confusable condition, $F(1, 25) = 6.07$, $p = .021$, $\eta_p^2 = .20$. There was no interaction between group and condition, $F(1, 25) = 0.23$, $p = .64$, $\eta_p^2 = .01$. Note that these results held regardless of whether d', raw accuracy, or false positive/ hit rate was analysed.

Nonword Knowledge. Performance on the yes/no recognition test for nonwords (Table 2) was measured by computing d' scores for each participant in the non-confusable and confusable condition. Overall, poor readers had lower d' scores than controls, $F(1,25) = 15.03$, $p = .001$, $\eta_p^2 = .36$. For both groups, d' scores were lower in the confusable then the non-confusable condition $F(1, 25) = 15.48$, $p = .001$, $\eta_p^2 = .38$. The interaction between group and condition was not significant, $F(1,25) = 1.49$, $p = .234$, $\eta_p^2 = .06$. Again, the pattern of results was consistent regardless of whether d', raw accuracy, or false positive /hit rate was analysed.

Visual-Verbal Associative Knowledge. The raw proportion correct for each participant is shown in Table 2. Both groups performed well above chance (25%) in each condition. All participants performed less accurately in the confusable than the non-confusable condition $F(1,25) = 12.23$, $p = .002$, $\eta_p^2 = .33$. Although there was a trend toward poorer performance by poor readers in both conditions, $F(1, 25) = 4.91$, $p = .036$, $\eta_p^2 = .16$, this did not survive the correction for multiple comparisons (adjusted $p = .058$). There was no interaction between group and condition, $F(1,25) = 0.08$, $p = .785$, $\eta_p^2 = .00$.

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Discussion

The current study aimed to specify the level at which phonological deficits in verbal PAL tasks occur in poor readers. To disentangle phonological input and phonological output, we employed a two-phase learning paradigm in which we first trained paired associates to criterion in the verbal-visual direction and subsequently tested knowledge in the visual-verbal direction.

Verbal-visual PAL

The first aim of the study was to determine whether poor readers are impaired in a verbal PAL task in the absence of phonological output demand. Previous work by Litt and Nation (2014) demonstrated that children with dyslexia are unimpaired in verbal-visual PAL, indicating that PAL deficits may be restricted to verbal output; however, the strength of this conclusion was limited by the use of nonword stimuli that were maximally distinct and potentially insensitive to the quality of phonological learning. To address this issue, we measured verbal-visual PAL using non-confusable and confusable nonwords. The rationale behind this manipulation was that detailed segmental representations of the nonwords would be necessary to perform well in the confusable PAL condition because no single phoneme or rime-unit could be used to discriminate a nonword from all others in the set.

The results for the non-confusable condition were clear: poor readers did not require more trials to learn the paired associates, nor were they less accurate than controls on the test of verbal-visual associative knowledge following training. These findings replicate those of Litt and Nation (2014) and add to the evidence that poor readers do not have general deficits in PAL or cross-modal associative learning (e.g., Aguiar & Brady, 1991; Kalashnikova, 2016; Vellutino et al., 1975). Moving to the confusable condition, the results showed that regardless of group membership, all children required more trials to reach criterion in comparison to the non-confusable condition. Together with the observation that the confusable condition

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captured more variance in performance than the non-confusable condition, this indicates that the manipulation of phonological confusability successfully increased task sensitivity. Despite this increased sensitivity, we did not find evidence for impaired verbal-visual PAL in poor readers. Consistent with the results of the non-confusable condition, verbal-visual learning proceeded at a similar rate and resulted in comparable accuracy levels (as measured by the verbal-visual associative knowledge test) in poor readers and controls.

Importantly, our results indicated that poor readers were not disproportionately hampered by phonological confusability (see also Messbauer & de Jong, 2006). Some researchers have proposed that poor readers should have particular difficulty with tasks utilizing phonological neighbours if phonological representations are insufficiently specified to distinguish between them (e.g., Elbro, 1996; Messbauer & de Jong, 2006). Although metrics such as "distinctness scores" and mispronunciation detection provide some evidence for less distinct phonological representations in children with dyslexia (Elbro, Borstrøm, & Petersen, 1998; Elbro & Jensen, 2005; Fowlert et al., 2004), a number of studies have failed to find a phonological confusability effect in dyslexia using phonological output tasks (Hall, Wilson, Humphreys, Tinzmann, & Bowyer, 1983; Johnston, Rugg, & Scott, 1987; Messbauer & de Jong, 2006; Ramus & Szenkovits, 2008; see also Mark, Shankweiler, Liberman, & Fowler, 1977). Our study adds to the evidence by showing that phonological confusability does not disproportionately hamper poor readers in a task requiring the acquisition of novel phonological representations. Discrepancies in the methods used across studies may account for the inconsistent findings regarding the distinctness of phonological representations in poor readers. Another possibility is that confusability effects are only present in children with severe deficits in phonological awareness. Our sample performed at the low end of the normal range on our standardized phonological measures, and thus may not have the severity of deficits in phonological awareness as children who show this effect in the literature.

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Visual-verbal PAL

The second aim of the study was to determine whether phonological output demand induces poor PAL performance when prior learning has been tightly controlled in a phonological input PAL task. Our design equated learning between poor readers and controls in verbal-visual PAL *before* requiring any verbal output, allowing us to assess the influence of phonological output on performance. We predicted that if poor readers have output-specific impairments, they should evidence visual-verbal deficits even after training to criterion in verbal-visual PAL.

The results showed that testing in the visual-verbal direction resulted in an initial decrease in accuracy for both groups, an expected consequence of testing in a direction opposite to that of encoding (e.g., Morris, Bransford, & Franks, 1977; Segal & Mandler, 1966). Yet despite having come to the task with verbal-visual performance matched to controls, poor readers were impaired in visual-verbal PAL from the very first trial. Moreover, even with corrective feedback and a strong foundation of prior learning via verbal-visual PAL, performance did not recover by the final test trials. Analysis of the errors in visual-verbal PAL confirmed that the impairment was phonological, rather than associative in nature. This replicates previous studies reporting that children with dyslexia commit a higher proportion of phonological errors than age-matched controls in visual-verbal PAL (Mayringer & Wimmer, 2000; Messbauer, de Jong, & van der Leij, 2002; Litt & Nation, 2014).

Not only did visual-verbal PAL deficits occur in spite of prior verbal-visual training to criterion, but the results also demonstrated that poor performance was not a consequence of individual differences in the quality of verbal-visual PAL. In a stringent series of analyses, we tested whether a participant's accuracy in visual-verbal PAL for a particular item was based on how quickly or accurately they had learned that item in verbal-visual training. Not surprisingly, there was a strong item-specific relationship between verbal-visual learning rate

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and subsequent visual-verbal accuracy, such that items that were learned in fewer trials were more likely to be accurately named in visual-verbal PAL. Likewise, items that were learned to a higher level of accuracy (as measured by the verbal-visual associative knowledge test) were also named more accurately in visual-verbal PAL. Yet even after accounting for this relationship, the deficit exhibited by poor readers in visual-verbal PAL not only remained in both conditions—it was just as robust. In other words, any subtle differences in the quality or rate of learning in verbal-visual PAL could not account for the substantial deficit observed in visual-verbal PAL. The pervasive nature of the impairment in visual-verbal PAL was further demonstrated by the fact that phonological confusability did not modulate the extent of the deficit. This suggests that the impairment is situated at a level in the phonological system that affects phonological output generally, even when the stimuli comprise simple distinct nonwords.

Together, these results are suggestive of difficulty specific to the phonological output component of PAL. Although it is possible that these results instead reflect a difficulty arising from the switch in the direction of testing (i.e., from verbal-visual to visual-verbal), this seems unlikely. Deficits in visual-verbal PAL are consistently reported in dyslexia, even when there is no switch in the direction of testing (i.e., both training and testing occur in the visual-verbal direction) (Litt & Nation, 2014; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Vellutino et al., 1975). Additionally, a switch in the opposite direction (i.e., from visual-verbal to verbal-visual testing of the same paired associates) does not negatively impact children with dyslexia; in fact, it eliminates deficits seen in the visual-verbal direction (Litt & Nation, 2014).

Here we must emphasise that our use of the term *phonological output* is broad. There are many processes involved in the phonological output component of PAL and our study was not designed to tease these apart. Output–specific processes such as mapping from

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abstract phonological representations to articulatory gestures and explicit access and retrieval of phonological representations have been proposed to be deficient in dyslexia (e.g., Catts, 1989; Hulme & Snowling, 1992; Ramus & Szenkovits, 2008; Shankweiler & Crain, 1986; Smith, Lambrecht Smith, Locke, & Bennett, 2006; Snowling & Hulme, 1994) and each of these accounts would be consistent with our data. Teasing these processes apart requires careful methods, and the view one takes on phonological output processes depends in part on the theoretical model one subscribes to (e.g., Allport, 1984; Harris & Coltheart, 1986; Martin & Saffran, 2002; Nickels & Howard, 1995; Monsell, 1987). Nevertheless, our data does allow us to rule out deficits in production (i.e., motor-planning or articulation) itself. Poor readers did not have difficulty with the immediate perception or repetition of the nonwords in our study (see also Litt & Nation, 2014; Mayringer & Wimmer, 2000), a finding that constrains our conceptualization of phonological output deficits to the processes that occur prior to motor/response planning and articulation.

Component Knowledge

Although the results discussed above were clear in demonstrating visual-verbal PAL deficits in the absence of verbal-visual PAL deficits, the interpretation of these results is complicated by the component knowledge tests. These knowledge tests were designed to assess knowledge of the symbols, nonwords, and associations in isolation, without requiring phonological output. Consistent with previous findings, children with reading difficulty did not demonstrate poorer knowledge of the symbols than controls (Litt & Nation, 2014, Messbauer & de Jong, 2003; Vellutino et al., 1975). Both groups showed good discrimination between target symbols and close visual foils, confirming that poor performance in visual-verbal PAL did not stem from difficulty learning the visual symbols. The groups also did not differ in associative knowledge, although there was a trend toward poorer performance in children with reading difficulty. In contrast to the results for symbols and associative

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knowledge, poor readers did demonstrate poorer knowledge of both the confusable and non-confusable nonwords than controls. This was unexpected given the results of the PAL tasks indicating that deficits only occurred under conditions requiring verbal output.

There are several potential explanations for these results. The first possibility is that the knowledge tests provide evidence that PAL deficits are in fact underpinned by deficient learning mechanisms that affect both phonological input and output. It is possible that despite the increased sensitivity afforded by the confusable verbal-visual PAL condition, the task was still not sensitive enough to reveal differences in the quality of phonological learning. By design, this task only involved phonological input, the limitation of which is that it can only measure the quality of the newly learned phonological representations via recognition. In contrast, visual-verbal PAL necessarily requires recall of the precise nonword, and thus likely provides a better index of the phonological representation that has been acquired. Although poor readers were not slower to learn in the confusable verbal-visual PAL condition, providing evidence of unimpaired associative learning mechanisms, we cannot rule out that they somehow achieved this learning with less well-specified representations of the nonwords. Perhaps the component knowledge check, in asking participants to distinguish between targets and close phonological foils, was more sensitive than verbal-visual PAL to the quality of representations that had been learned.

An alternative possibility is that learning was intact following verbal-visual PAL, but that the initial representations children had acquired were subsequently disrupted during visual-verbal PAL, leading to poorer performance on the knowledge test. Recall that the component knowledge checks were administered at the conclusion of the experiment. Prior to this point, there was no indication of deficits in verbal-visual PAL, a dynamic measure of learning. It was only following visual-verbal PAL that deficits emerged. This leaves open the possibility

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that poor performance on the nonword knowledge test may have been a *consequence* of the phonological output deficits experienced in visual-verbal PAL.

Although both groups were matched for rate and accuracy in verbal-visual PAL before testing in visual-verbal PAL, they were not trained to 100% accuracy. Thus further learning of the phonological representations would have occurred during visual-verbal PAL. It has been proposed that feedback from speech production to speech perception plays an important role in adjusting phonological representations (e.g., Houde & Nagarajan, 2011; MacDonald, Johnson, Forsythe, Plante, & Munhall, 2012; Tourville & Guenther, 2011; Villacorta, Perkell, & Guenther, 2007). Taking this interactivity into account, it is possible that although poor readers acquired phonological representations normally during verbal-visual PAL, these fragile representations became contaminated via inaccurate and inconsistent feedback from phonological output during visual-verbal PAL. In accordance with this view, studies have shown that the production of errors during word learning negatively affects performance in subsequent recognition tasks (e.g., Baddeley & Wilson, 1994; Warmington, Hitch, & Gathercole, 2013), and memory traces for errors produced during learning can interfere with existing memory traces for target words (Page, Wilson, Shiel, Carter, & Norris, 2006).

Ultimately, we can only speculate on the cause of poorer performance in the nonword knowledge test. It is recommended that future studies administer a test of nonword knowledge immediately following verbal-visual PAL, before any influence from phonological output has occurred. This will speak to the question of whether poorer nonword representations are a cause or consequence of difficulty in verbal-output PAL. Additionally, although our manipulation of phonological confusability did not reveal group differences in verbal-visual PAL, alternative manipulations may be better able to probe the quality of phonological representations acquired during this task. For example, testing verbal-visual knowledge under speech-in-noise (immediately following training) may provide the

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sensitivity necessary to detect subtle differences in the quality of phonological representations.

Limitations and Conclusions

It is important to acknowledge that the results of this study are based on a small sample size. This may inflate the effect sizes reported for significant results. Although we did our best to address this issue (by using analyses that result in the best possible power given our sample size and adjusting for multiple comparisons), further studies with larger sample sizes are needed to replicate these effects. Additionally, our sample of poor readers may be less impaired overall than samples drawn from clinical populations of children with dyslexia. This could influence the size of the effects seen in this study. That being said, by selecting participants based only on reading ability and not on the presence of specific cognitive deficits (i.e., phonological awareness, RAN), we did not bias our results toward a specific profile of poor reader or increase the likelihood of finding a phonological locus of PAL deficits. Additionally, our selection criteria required pervasive reading difficulty across multiple subskills of reading (i.e., mixed profile), making our sample highly representative of the heterogeneous population of children with reading difficulty (Castles & Friedmann, 2014;Griffiths & Snowling, 2002; Manis & Bailey, 2008; McArthur et al., 2013; Pennington, 2006; Peterson, Pennington, & Olson, 2013; Ramus, 2004; Ziegler, Castel, Pech-Georgel, Alario, & Perry, 2008).

Heterogeneity is an important issue to take into account when interpreting research on reading disabilities, as it is unlikely that a single deficit characterises all children with poor reading. This is the case even if we constrain this discussion to phonological deficits. The phonological system is multifaceted (e.g., Cunningham, Witton, Talcott, Burgess, Shapiro, 2015; Wagner, Torgesen, Rashotte, & Pearson, 2013*),* and abilities such as phonological learning, phonological retrieval, phonological memory, and phonological awareness should

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not be assumed to be synonymous. Children may show different patterns of phonological impairments and these may, in turn, have different effects on the development of reading and language. Though our findings speak to poor readers as a whole, we do not wish to imply that every individual will show the same pattern of impairment. Mapping heterogeneity in phonological deficits onto different reading profiles is an important next step for research.

To summarise, the current study demonstrated that poor readers are disproportionately hampered by phonological output PAL tasks, even when prior learning has been matched to controls in an analogous phonological input PAL task. The weight of our evidence favours output-specific phonological processes as the source of this difficulty, a conclusion echoed by the literature (Kalashnikova & Burnham, 2016; Litt & Nation, 2014; Torgesen & Murphy, 1979; Vellutino et al., 1975). However, the results of the nonword knowledge check indicated that poor readers may have had less precise phonological representations of the nonwords. Our design did not allow us to determine whether this was a cause or a consequence of difficulty in the phonological output PAL task because the nonword knowledge test was administered following both PAL tasks

Regardless of the source of the difficulty on phonological output tasks, our results have important implications for clinicians and educators. When assessing children with reading difficulty, different profiles of performance may emerge depending on whether skills are measured using phonological input or phonological output tasks. The majority of the assessment tools used in educational and clinical settings require verbal responses. It cannot be assumed that deficits observed on these tasks reflect deficient learning or a lack of knowledge. Pinpointing the source of a deficit will require the use of sensitive indices of the underlying skill of interest, using both phonological input and output tasks.

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Supplementary Material

The Supplementary Material (Appendix A and Supplementary Materials) is available at:

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Figure Captions

Figure 1. Overview of the PAL procedure. Cursors in the stimulus column indicate that a click on the symbol or speaker icon was necessary to initiate auditory presentation. Cursors in the response column indicate selection of the response. Please note that the ear and mouth images are for illustrative purpose only and were not visually presented in the task.

Figure 2. Average trials to criterion for each group and condition (collapsed across items) in verbal-visual PAL. Larger data points indicate overlap in individual data.

Figure 3. Proportion correct in visual-verbal PAL across blocks.

Error bars represent 95% confidence intervals around the individual means.

Note that these confidence intervals should not be used to make inferences about the contrasts tested in the models as they do not reflect the correlations between factors. For statistics taking the between and within-subjects variance into account, please refer to the mixed effects model results for visual-verbal testing.

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Table 1. Descriptive characteristics of poor readers and controls

	Poor Readers		Controls			
	M	SD	M	SD	t	Cohen's *d*
Age (years)	10.04	1.10	9.67	.78	-1.04	0.39
Nonverbal Reasoning[a]	51.86	5.43	56.29	8.29	1.67	0.63
Phoneme Deletion[b]	7.86	2.82	9.86	2.82	1.87	0.71
Nonword Repetition[b]	8.50	1.65	10.50	2.14	2.77*	1.05
Processing Speed[b]	10.00	2.39	11.29	2.84	1.30	0.49
RAN Letters[c]	29.71	8.02	23.62	5.43	-2.35*	0.89
RAN Digits[c]	32.31	8.29	27.39	7.01	-1.69	0.64
Sight Word Fluency[d]	80.43	11.58	107.29	11.17	6.25***	2.36
Nonword Fluency[d]	80.29	14.92	108.93	9.03	6.14***	2.32
Regular Words[e]	-1.60	0.49	0.73	0.67	10.49***	3.97
Irregular Words[e]	-1.14	0.69	0.53	0.60	6.77***	2.58
Nonwords[e]	-1.93	0.52	0.50	0.66	10.83***	4.09

Note. [a] *T*-score, $M = 50$, $SD = 10$; [b] Scaled Score, $M = 10$, $SD = 3$; [c] Total time (in seconds); [d] Standard Score, $M = 100$, $SD = 15$; [e] *Z*-score, $M = 0$, $SD = 1$
*$p < .05$, ***$p < .001$

Table 2.

Mean (SD) performance on the component knowledge tests

		Poor Readers	Controls
Non-confusable	Verbal-Visual Associations[a]	.66 (.26)	.78 (.31)
	Symbols[b]	2.07 (.49)	2.29 (.38)
	Nonwords[b]	1.88 (.46)	2.24 (.39)
	Visual-Verbal Associations[a]	.62 (.34)	.82 (.24)
Confusable	Verbal-Visual Associations[a]	.43 (.27)	.38 (.31)
	Symbols[b]	1.64 (1.07)	2.00 (.56)
	Nonwords[b]	1.01 (.72)	1.78 (.68)
	Visual-Verbal Associations[a]	.39 (.22)	.56 (.31)

Note. [a]Proportion correct; [b]d-prime

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Table 3.
Proportion of visual-verbal errors by type

	Poor Readers		Controls	
	M	SD	M	SD
Associative	.31	.18	.62	.28
Phonological	.69	.18	.38	.27

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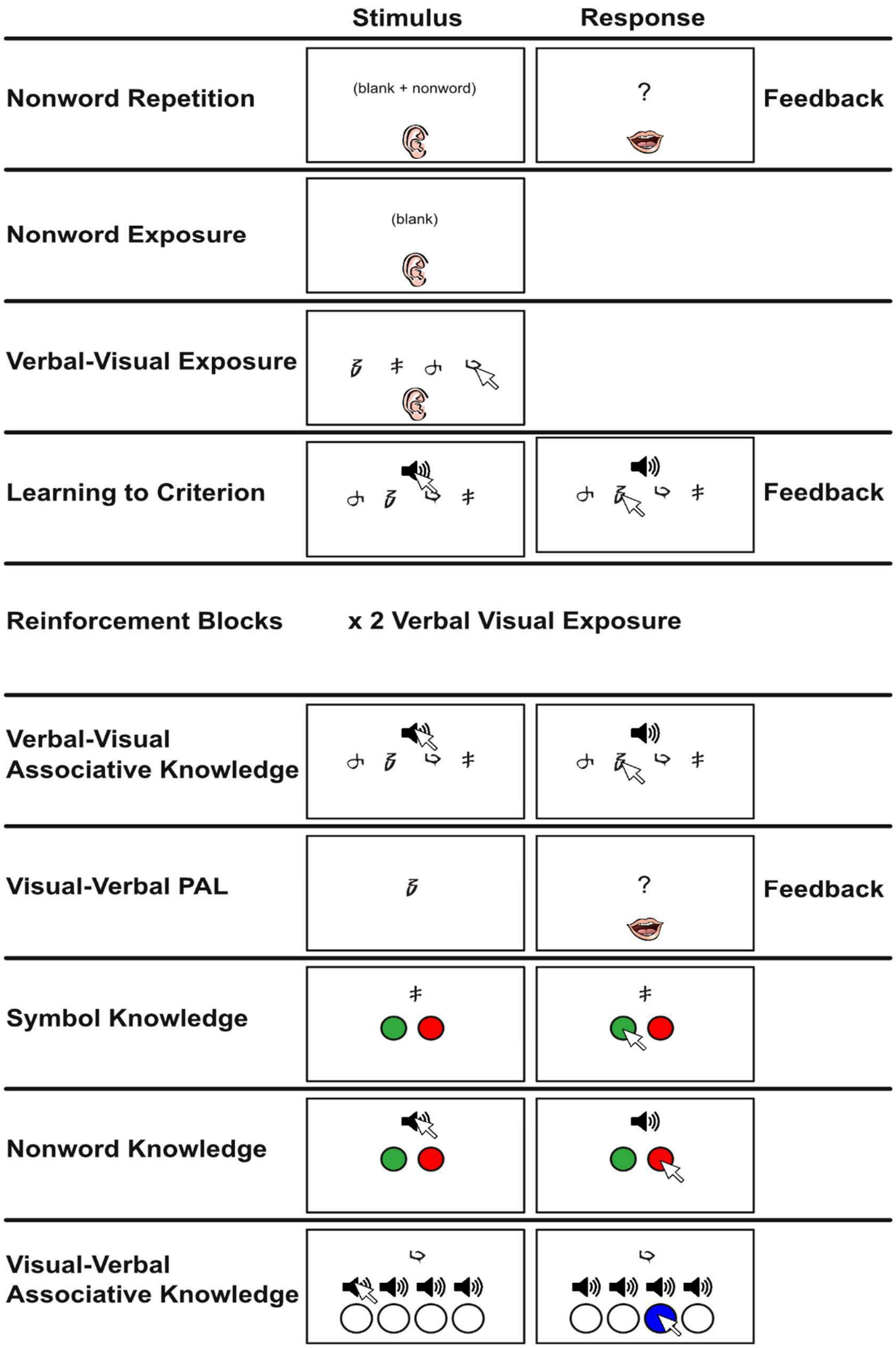

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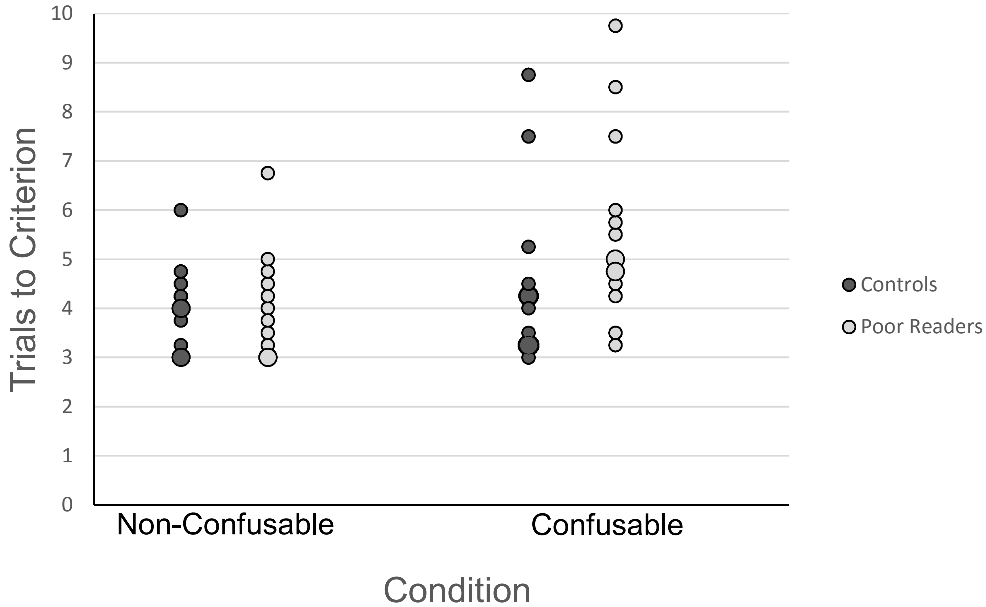

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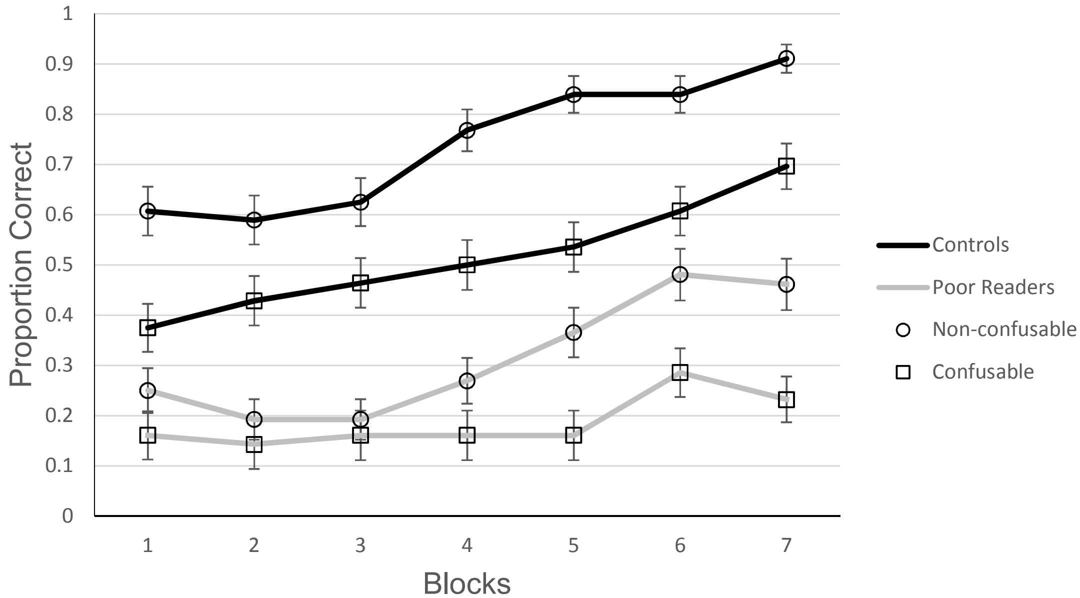

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APPENDIX A

Table A.1

Nonword Stimuli and Recognition Test Foils

Non-Confusable Nonwords	Non-Confusable Foils	Confusable Nonwords	Confusable Foils
Yut	Yud	Zib	Zeb
Mif	Mef	Vek	Vik
Vog	Veg	Zek	Zik
Teb	Tep	Vib	Veb

Table A.2

Pool of PAL Symbols and Recognition Test Foils

Symbols	Foils

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