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Exploring factors underlying children's acquisition and retrieval of sound–symbol association skills

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ABSTRACT

Letter knowledge is considered an important cognitive foundation for learning to read. The underlying mechanisms of the association between letter knowledge and reading skills are, however, not fully understood. Acquiring letter knowledge depends on the ability to learn and retrieve sound–symbol pairings. In the current study, this process was explored by setting preschool children's ($N = 242$, mean age = 5.57 years) performance in the acquisition and retrieval of a paired associate learning (PAL) task in relation to their letter knowledge as well as to their performance in tasks assessing precursors of reading skills (i.e., phonological awareness, rapid automatized naming, phonological short-term memory, backward recall, and response inhibition). Multiple regression analyses revealed that performance in the acquisition of the PAL task was significantly associated with phonological awareness and backward recall, whereas performance in the retrieval of the PAL task was significantly associated with rapid automatized naming, phonological awareness, and backward recall. Moreover, PAL proved to be mediating the relation between reading precursors and letter knowledge. Together, these findings indicate that the acquisition of letter knowledge may depend on a visual–verbal associative learning mechanism and that different factors

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contribute to the acquisition and retrieval of such visual–verbal associations.

Introduction

Learning to read is assumed to depend on phonological representations and a unique crossmodal associative learning process of mapping orthographic and phonological units. The process of mapping is critical for learning letter–sound correspondences at the level of single letters, letter groups, and whole words when acquiring a word recognition system (Hulme and Snowling, 2013). Basically, paired associate learning (PAL) tasks, which require (a) pairing of a stimulus and response item in memory and (b) retrieval of these pairings from memory, are thought to tap this associative learning mechanism. Evidence indeed suggests that visual–verbal PAL (i.e., pairing a visually presented symbol with a verbal output) shares a robust and specific relationship with reading abilities (Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Litt, de Jong, van Bergen, & Nation, 2013; Litt & Nation, 2014). Differences in PAL abilities have been demonstrated between children with dyslexia and those without dyslexia (Messbauer and de Jong, 2003; Wimmer, Mayringer, & Landerl, 1998) as well as in studies predicting reading skills with PAL (e.g., Georgiou, Liu, & Xu, 2017; Hulme et al., 2007; Lervåg, Bråten, & Hulme, 2009; Poulsen & Elbro, 2018).

Although significant work has been carried out to clarify the relationships between PAL and reading, only few studies examined the factors underlying sound–symbol association skills (e.g., de Jong, 2007; Windfuhr & Snowling, 2001). More specifically, to our knowledge, no study exists examining possible differences in factors underlying the acquisition and retrieval of new sound–symbol pairs. The current study, therefore, investigated the relationships between the acquisition and retrieval of sound–symbol pairs and other cognitive skills associated with the acquisition of reading skills in a sample of pre-kindergarten children.

PAL can be seen as a basic learning mechanism that requires the storage and retrieval of 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, verbal–visual). In the context of reading, crossmodal PAL, defined as any association requiring a connection between a visual stimulus and a verbal stimulus, is in the focus of interest (Lervåg et al., 2009; Litt et al., 2013; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). The association and retrieval of letter names and sounds or learning of sight vocabulary—that is, an association of printed words with their pronunciations—are excellent examples of crossmodal PAL. This may be especially true for irregular sight words in deep orthographies such as English (Hulme et al., 2007; Windfuhr & Snowling, 2001). Finally, reading can also be seen as a form of crossmodal visual–verbal PAL, particularly in the early stages of development (Litt et al., 2013).

The empirical implementation of the visual–verbal PAL paradigm has a similar format. The visual stimuli, which can be abstract symbols (e.g., a dot; Horbach, Scharke, Cröll, Heim, & Günther, 2015), photographs (e.g., of children; Mayringer & Wimmer, 2000), drawings (e.g., cartoon animals; Poulsen & Elbro, 2018), and unfamiliar letters (e.g., Greek, Hebrew, and Arabic; Lervåg et al., 2009) or even letters of extinct languages (e.g., Akkadian; Litt et al., 2013), are presented together with the verbal stimuli, which are usually names, nonword names, or syllables. Thus, differences in the complexity of the stimulus material are found, which is mainly due to the adaptation of the tasks to the respective age range of the participants. Irrespective of the exact stimuli, performance on any PAL paradigm depends on successful learning of three distinct components, namely the visual stimulus, the verbal stimulus, and the association between these two items. Individual performance differences, thus, may stem from processes operating at any of these three levels (Litt et al., 2013). Moreover, individuals may differ with regard to their ability to retrieve learned associations from memory. Accordingly, the question arises as to which individual abilities are responsible for individual differences in visual–verbal PAL tasks.

Because reading can also be classified as a form of crossmodal visual–verbal PAL, it is reasonable to assume that skills that are of importance for reading acquisition may also be crucial for PAL performance. There is some empirical evidence supporting this suggestion. For instance, de Jong, Seveke, and van Veen (2000) asked children to associate non-names with cuddly toys. They found that measures of phonological awareness, letter knowledge, and phonological short-term memory (nonword repetition) were related to performance in the PAL task. In addition, the findings implicated a direct role of phonological awareness in the development of visual–verbal PAL ability, namely that training in phonological awareness improved visual–verbal PAL performance in kindergartners (de Jong et al., 2000). Correspondingly, Windfuhr and Snowling (2001) found that the performance of English school children on a phonological awareness test was a strong predictor of their ability to map abstract visual shapes with spoken nonwords, whereas the children's phonological memory explained no further variance in PAL. Similarly, the results of de Jong (2007) showed that individual differences in phonological awareness strongly affected letter–sound learning even after current letter knowledge was controlled. In the study of Lervåg et al. (2009), PAL, measured by three tests in which kindergarten children learned to pair three nonword names with three pictures, was associated with the phonological skills of phonological awareness, phonological working memory, letter knowledge, and rapid automatized naming (RAN) and particularly with verbal abilities. Less strong correlations were reported by Litt et al. (2013), who requested school-aged children to map abstract symbols of the extinct language Akkadian with nonwords. The performance in this PAL task was only moderately related with phonological awareness, whereas no significant correlation was found with RAN (see also Georgiou et al., 2017; Poulsen & Elbro, 2018; Poulsen, Juul, & Elbro, 2015).

Differences in stimulus type may modulate the relationships between PAL performance and other reading precursors. For example, complex material may require more phonological working memory capacity; clearly distinguishable nonwords may be less stressful for phonological awareness, and regular words, for which lexical entries exist, may require little phonological skills when mapping to new symbols is requested (cf. de Jong et al., 2000). Inconsistent results concerning the relationship of PAL with phonological skills may also be due to the age of the participants. For instance, higher correlations between phonological skills and PAL are found in studies with children prior to formal reading instruction than in studies with school-aged children. Another issue that might have led to differences in the associations with other variables across studies is measurement error and the use of observed versus latent variables. Except for the study by Lervåg et al. (2009; partly also Litt et al., 2013), PAL performance and most of the other reading precursor skills were adopted as observed variables (de Jong et al., 2000; Georgiou et al., 2017; Hulme et al., 2007; Mourgues et al., 2016; Poulsen & Elbro, 2018; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001).

However, phonological and other reading precursor skills may also contribute differentially to various phases of PAL tasks, that is, a phase with corrective feedback (learning phase) and a phase without corrective feedback (retrieval phase). For example, RAN as an indicator of efficient retrieval of phonological codes from long-term memory proved to be less important in learning of phonological codes (e.g., de Jong, 2007). In a retrieval phase where no feedback is provided, the efficient retrieval of phonological codes from long-term memory may be more important. Moreover, research shows that central executive skills, such as updating and manipulating captured by backward recall, are of particular importance for acquiring new knowledge, whereas they play a minor role when knowledge is automatically accessed and well learned (Baddeley, 1996). Accordingly, in the retrieval phase of the PAL paradigm, the more passive storage mechanisms of the phonological short-term memory should be sufficient and the central executive skills of updating and manipulating are less relevant. However, it could also be argued that an adaptive cognitive control system for selecting relevant information is especially necessary in the retrieval phase. For example, when confronted with a particular symbol in the PAL paradigm, irrelevant information needs to be discarded and the correct sound needs to be named. Thus, it can be assumed that poor performance in the retrieval phase of the PAL paradigm may also be attributed to inefficient inhibitory mechanisms. So far, no data are available regarding this research question because existing studies do not distinguish between a learning phase and a retrieval phase. Apart from de Jong et al. (2000), researchers have provided corrective feedback when investigating PAL abilities (de Jong, 2007; Georgiou et al., 2017; Hulme et al., 2007; Lervåg et al., 2009; Mourgues et al., 2016; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). Alternatively, the correct answer was presented regardless of the accuracy of the response (Litt et al., 2013; Litt & Nation, 2014). Because backward recall and inhibition abilities have not been put into relation to PAL abilities, it is still not clear whether these abilities are of importance for the acquisition and/or retrieval of new sound–symbol pairs.

When considering the relation between reading precursor skills and PAL tasks, the relation between letter knowledge and PAL deserves attention. This can be viewed from two perspectives. On the one hand, PAL is required to establish letter knowledge. On the other hand, pronounced letter knowledge may facilitate learning new sound–symbol pairs because knowledge of the alphabetic principle is available, that is, the understanding that the letters in printed words map onto the phonemes in spoken words (Byrne, 1998). However, because variance in letter knowledge is rarely found in studies with children after the start of formal reading instruction, only a few PAL studies have also assessed letter knowledge. For example, de Jong (2007) found low correlations between sound (re)learning and letter knowledge ($r = .24$ and $r = .25$), de Jong et al. (2000) found a moderate correlation ($r = .34$) between the ability to associate non-names with cuddly toys and letter knowledge, and Lervåg et al. (2009) reported a rather high correlation ($r = .57$). Thus, it is not sufficiently clear how much variance PAL abilities and letter knowledge share with each other and whether the association with letter knowledge is comparable for both performance in the learning phase and performance in the retrieval phase of the PAL paradigm.

Although letter knowledge may predict PAL abilities, it is more reasonable to assume that PAL predicts letter knowledge because PAL tasks simulate the building of lexical entries for sound–symbol pairs in long-term memory. That is, PAL may be considered as the process of acquisition, whereas letter knowledge should be considered as the result of this process. Thus, PAL abilities may act as a mediator when considering the interplay of different reading precursor skills and letter knowledge. According to de Jong and Olson (2004), letter learning involves (a) the formation of a temporary phonological representation of a letter name or sound in phonological memory and (b) the association of this representation with the form of the respective letter and its storage in long-term memory. In accordance with the finding that phonological short-term memory is involved in the acquisition of novel phonological representations (Baddeley, 1996; de Jong & Olson, 2004), the simultaneous acquisition of several sound–symbol pairs may capture more phonological short-term memory capacity compared with letter knowledge tasks where lexical entries are built over a longer period of time. Phonological short-term memory, thus, may influence letter knowledge more indirectly via PAL abilities. Moreover, the association of temporary phonological representations with the form of letters and its storage in long-term memory is considered as pure association learning (de Jong & Olson, 2004). As suggested by de Jong and Olson (2004), RAN reflects association learning and, therefore, contributes to the acquisition of letter knowledge. However, whereas RAN should rather be considered as the product of associative learning processes, performance in a PAL task can be taken as an indicator of associative learning processes per se. Accordingly, RAN may also influence letter knowledge indirectly via PAL abilities. Because only a few studies of PAL have assessed letter knowledge, it is still an issue whether PAL abilities mediate the relation between the different phonological and other reading precursor skills, on the one hand, and letter knowledge, on the other.

The current study

The aim of the current study was to explore which cognitive factors underlie sound–symbol association skills. In detail, we wanted to find out (a) whether the same cognitive predictors are of importance for both the learning and retrieval of new sound–symbol associations, (b) whether the association with letter knowledge differs for the learning and retrieval phases of the PAL paradigm, and (c) whether PAL performance mediates the association between specific reading precursor skills and letter knowledge. In addition, we used latent variables to avoid the potential confounding of measurement errors that might have happened in several of the earlier studies using observed variables (Cole & Preacher, 2014). This is particularly important because the reliability of PAL tasks, indicated by Cronbach's alpha, can be called into question (Poulsen et al., 2015).

Based on findings from previous studies (Mourgues et al., 2016; Windfuhr & Snowling, 2001) and the notion that awareness of the phonological structure of spoken words facilitates the creation of new phonological representations (de Jong, 2007), we hypothesized phonological awareness and phonological memory to be of particular importance for the learning phase and RAN, phonological memory, and response inhibition to be of importance for the retrieval phase. In addition, we expected PAL abilities to mediate the relation between the different reading precursor skills and letter knowledge.

Method

Participants

Data collection was carried out in the context of the TRIO project, which examines the effects of language education in kindergartens in the area of Frankfurt am Main, Germany. The study was commissioned by the German Federal Ministry of Education and Research (BMBF). Parents of participating children provided written informed consent prior to participation. In total, 247 children took part (all nonreaders). The mean age of the sample was 5;7 (years;months) (*SD* = 0;4), and the percentages of girls and boys were 46.6% (*n* = 115) and 53.4% (*n* = 132), respectively. The sample was composed of 131 monolingual German children, 47 simultaneously bilingual children, and 68 successively bilingual children (language information was missing for 1 child). Data collection was distributed over three sessions, each lasting up to 45 min. Because 5 children refused to participate in nearly all tests, our analyses are based on data from 242 children.

Instruments

Paired associate learning

PAL was measured by using a computer-based paradigm (see Horbach et al., 2015) in which children learn to pair three syllables with three symbols (learning phase) and to retrieve the newly learned associations (retrieval phase). The task started by introducing the three symbols: a triangle (▲), a square (■), and a circle (●). Each symbol was presented separately in the middle of the 14.1-inch screen. Children were told that the triangle was called /pa/, the square was called /ma/, and the circle was called /ta/. Children were then instructed to name the symbols. In the learning phase, each symbol was presented 10 times in an alternating but fixed order. If children responded correctly, they received positive feedback (e.g., "Yes, this was /pa/") and the next trial appeared. If children responded incorrectly, the experimenter provided corrective feedback (e.g., "No, this was /pa/"). A score of 1 point was given each time children remembered a name correctly (maximum score = 30). The retrieval phase was reached independently from the number of correctly solved trials in the learning phase.

The retrieval phase required children to apply the newly learned sound–symbol correspondences. In this phase, 12 trials were presented in the same way as in the learning phase except that feedback was no longer given (see Fig. 1). The retrieval phase started immediately after the learning phase and was discontinued after seven errors were committed. The internal consistency of both the learning and retrieval phases was .90 (Kuder–Richardson 20 test).

Rapid automatized naming

The RAN task consisted of two nonalphanumeric subtests and assessed naming speed for colors (green, yellow, red, blue, and black), and objects (tree, dog, ball, fish, and ice) (items adapted from Preßler, Könen, Hasselhorn, & Krajewski, 2013). In each subtest, items were arranged randomly in two rows of 10 on a sheet of white paper (A4). Children's task was to name all items as quickly as possible while making as few errors as possible. Naming time (in seconds) served as the dependent variable, with lower scores indicating higher performance. Each subtest was preceded by a short practice trial (i.e., one row with 5 items) to familiarize children with the material.

Phonological short-term memory and central executive

To assess the phonological short-term memory and central executive skills of updating and manipulating, four subtests from the computerized and adaptive Arbeitsgedächtnistestbatterie für Kinder

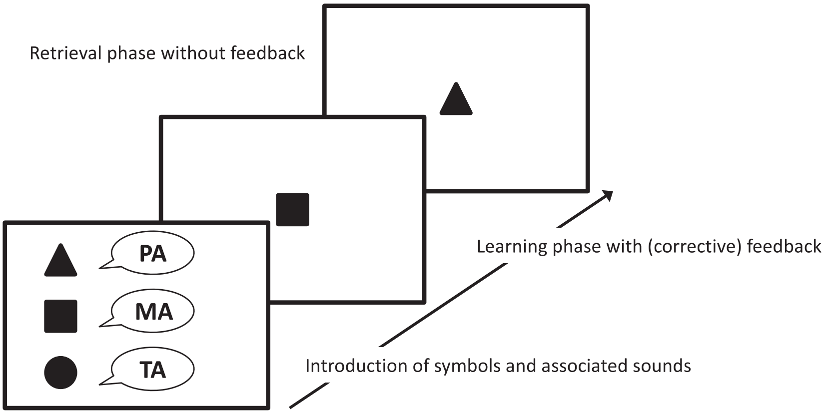

Fig. 1. Graphical representation of the task procedure of the PAL paradigm.

von 5 bis 12 Jahren (AGTB 5–12; Hasselhorn et al., 2012) were administered. The AGTB 5–12 is a German computerized test battery that assesses working memory functioning according to Baddeley's (1986) multicomponent model and shows good construct validity (Michalczyk, Malstädt, Worgt, Könen, & Hasselhorn, 2013) and criterion validity with respect to reading and spelling tests (Hasselhorn et al., 2012). Both phonological short-term memory and the central executive skills of updating and manipulating were assessed with verbal span procedures, differing only with respect to the order of recall: forward recall (phonological short-term memory) and backward recall (updating and manipulating). That is, in the phonological short-term memory part, children's task was to repeat the sequence orally in the same serial order as presented; in the backward recall part, the sequence needed to be reproduced immediately in the reverse order. Specifically, we assessed memory spans for digits and words, respectively. In the digit span task, increasing sequences of different digits were presented audibly at the rate of one digit every 1.5 s, with no digit appearing twice in a particular sequence. Similarly, the word span task required the serial repetition of high-frequency words that were presented audibly at the rate of one word every 1.5 s. Word sequences were constructed out of nine phonologically and semantically dissimilar German monosyllabic nouns. Each word appeared only once within a particular sequence.

All four tasks were span measures with an adaptive testing procedure. They consisted of 10 trials divided into five testing blocks with 2 trials each. The first testing block started with a 2-item sequence, and sequence length was adjusted after each response. If children recalled the presented trial correctly, the sequence length of the subsequent trial increased by 1 item. If, however, children's recall was incorrect, the sequence length of the next trial decreases by 1 item (or remained at the 2-item sequence). In the remaining four testing blocks, the sequence length was adjusted more conservatively as follows. If children recalled both trials of the testing block correctly, the span length of the next block increased by 1 item. If the recall was incorrect for only 1 of the 2 trials, the span length remained the same. If, however, children recalled both trials incorrectly, the span length decreased by 1 item. The calculation of the span score was based on the mean performance of all testing blocks (the last 8 trials). For each correct response, children received a score that corresponded to the span length. For instance, if children correctly recalled a 4-item sequence, they received 4 points. A false response was assigned the span length decreased by 1 item (e.g., incorrect repetition of a 4-item sequence resulted in 3 points only).

Phonological awareness

Phoneme deletion was used to assess phonological awareness. The task comprising drawings of seven familiar words (e.g., house, fork) was adapted from the Comprehensive Test of Phonological Processing battery (Wagner, Torgesen, and Rashotte, 1999). At the beginning of each trial, children were asked to name the drawing to ensure that they were familiar with the word. Then, the task required children to first name the initial phoneme of the word (phoneme detection; e.g., “Wal” →/w/) and, next, to say the word without saying the initial phoneme (rest word; e.g., “Wal” without /w/ becomes “al”). The internal consistency was .87 for the phoneme detection task and was .80 for the rest word task (Kuder–Richardson 20 test).

Response inhibition

A computerized go/no-go task, based on the paradigm of Berlin and Bohlin (2002), was used to test children’s ability to inhibit a prepotent response. Children were shown a red square, a red triangle, a blue square, and a blue triangle one at a time on a computer screen (stimulus presentation: 800 ms; response interval: 1700 ms). Altogether, the task consisted of four blocks with 30 trials with a “go rate” of 70%. In Blocks 1 and 3, children were instructed to press a key (“go”) as soon as possible whenever one of the blue shapes appeared on the screen but to press no key (“no-go”) whenever one of the red shapes appeared. The same stimuli were used for Blocks 2 and 4, but children were then instructed to press a key every time they saw a square and to inhibit their response every time they saw a triangle irrespective of color. The score derived from the task was the sensitivity parameter A', a nonparametric measure according to signal detection theory, which takes the hit and false alarm rate into account and which typically ranges from .5, indicating that signals cannot be distinguished from noise, to 1, corresponding to perfect performance (Stanislaw & Todorov, 1999).

Letter knowledge

This task comprised the 12 most common German letters (E, N, I, R, A, T, S, H, D, U, L, and C), each of which was presented separately on a white sheet of paper. Children’s task was to provide the corresponding letter name. In German, the names of the vowels correspond to the sounds. Most consonant names contain corresponding letter sounds, either as initial phoneme following the acrophonic principle (H, D, and T) or as final phoneme (R, L, S, and N). Only the consonant name of C is inconsistently related to letter sounds. Children received 1 point for each correctly pronounced letter (both letter names and letter sounds were possible answers).

Procedure

Testing was done in three sessions (distributed over 3 days). Children were tested individually at a child day-care center in a quiet room by trained university students. In the first session, the task for RAN was administered (together with some games for the purpose of getting to know each other and avoiding a test atmosphere). In the second session, the tasks for backward recall, PAL, and letter knowledge were administered. In the third session, the tasks for response inhibition and phonological awareness were administered.

Statistical analyses

To avoid measurement error, latent variables were used. First, a regression model with latent variables was evaluated with PAL learning and retrieval phases as separate but correlated dependent variables. In these structural equation models (SEMs), regression paths were evaluated from every predictor to the dependent variable and correlations between the predictors were permitted. Second, we applied confirmatory factor analysis (CFA) to compare the latent correlations between the PAL learning and retrieval phases with letter knowledge. To check whether the correlation between letter knowledge and PAL learning phase is comparable to the correlation between letter knowledge and PAL retrieval phase, the correlations were set to be equal and compared with a free estimating model. In a third step, an SEM was evaluated to explain variance in letter knowledge, the cognitive predictors mediated by PAL.

We used Mplus 8.0 (Muthén & Muthén, 1998–2017) to estimate latent variable models with missing data. To estimate the models, the robust full information maximum likelihood method MLR was used. This estimation method allows data from all individuals to be included regardless of their pattern of missing data (Rubin, 1974). To evaluate the goodness of fit for the CFA and SEM, we used the chi-square test statistic and several commonly recommended descriptive measures of model fit (Hu &

Bentler, 1998): the standardized root mean squared residual (SRMR) and the root mean square error of approximation (RMSEA) as well as the comparative fit index (CFI) and the Tucker–Lewis index (TLI). Models were evaluated as fitting well when the baseline fit indices (SRMR and RMSEA) were less than .08 and the incremental fit index (CFI) was .95 or greater. To examine differences in correlations and regression weights, we report Wald tests (instead of chi-square difference-based tests). Preacher and Hayes's (2008) bootstrapping technique (with 1000 resamples), which allowed us to establish confidence intervals (CIs), was used to test possible indirect effects more adequately.

Results

Descriptive statistics and latent correlations for all variables are found in Tables 1 and 2. The mean score for the PAL learning phase, where a maximum score of 30 was possible, was 12.50 ($SD = 7.29$), and the mean score for the retrieval phase, with a maximum score of 12, was 5.70 ($SD = 3.70$). Of the 12 letters, participants named a mean of 4.98 ($SD = 4.04$) letters correctly. To obtain indicators of the latent PAL factors, three item parcels were constructed, that is, the sum of the responses to the different symbols. The factor loadings and residuals were fixed to be equal across parcels. Correlations between the residual variances of the same indicators (e.g., the symbol named "pa") were allowed but fixed to be equal. The correlations were constrained to be equal. The latent correlations of the different variables are based on a CFA, $\chi^2(141) = 231.500$, $p < .05$, CFI = .928, TLI = .940, RMSEA = .051, SRMR = .069.

Explaining variance in the PAL learning and retrieval phases

To find out whether the same cognitive predictors are of importance for the learning and retrieval of new sound–symbol associations, an SEM with the PAL learning phase and the PAL retrieval phase as separate but correlated dependent variables was carried out. In this model, identification was achieved by fixing the factor loadings of each predictor to the same value and fixing the variance to 1. This was done to test for possible differences (see Kwan & Chan, 2011). Moreover, the residuals of the different indicators of each factor were constrained to be equal (e.g., the residuals of the digit

Table 1
Numbers of participants, means, standard deviations, Min, Max, skewness, and kurtosis for all variables.

	n	*M*	*SD*	Min	Max	Skewness	Kurtosis
PAL learning phase	232	12.50	7.29	0	29	0.27	−0.81
PAL retrieval phase	203	5.70	3.68	0	12	0.19	−1.13
Letter knowledge	219	4.98	4.04	0	12	0.16	−1.13
Phonological awareness							
Phoneme detection	217	2.15	2.40	0	7	0.70	−0.93
Rest word	217	0.84	0.84	0	7	2.13	3.62
RAN							
Objects	240	25.67	7.18	12.89	64.60	1.63	4.50
Colors	239	26.65	8.18	13.20	53.95	1.10	1.13
Response inhibition							
Block 1	232	.91	.13	.23	1.00	−3.06	10.96
Block 2	223	.86	.16	.17	1.00	−2.05	4.67
Block 3	228	.88	.13	.35	1.00	−2.08	4.73
Block 4	224	.82	.18	.23	1.00	−1.41	1.23
Phonological short-term memory							
Word span	239	2.65	0.66	1	4.38	−.45	.46
Digit span	235	2.76	0.72	1	4.75	−.20	.23
Backward recall							
Word span	228	1.82	0.52	1	3.13	−.21	−.76
Digit span	228	1.74	0.60	0	3.25	−.37	.49

Note. PAL, paired associate learning; RAN, rapid automatized naming.

Table 2
Estimated correlations between the latent variables.

	1	2	3	4	5	6	7
1. PAL learning phase	–						
2. PAL retrieval phase	.86	–					
3. Letter knowledge	.42	.49	–				
4. Phonological awareness	.50	.39	.49	–			
5. RAN	−.45	−.35	−.31	−.26	–		
6. Response inhibition	.26	.35	.21*	.31	−.41	–	
7. Phonological short-term memory	.34	.30	.32	.40	−.38	.47	–
8. Backward recall	.57	.56	.37	.37	−.56	.53	.59

Note. PAL, paired associate learning; RAN, rapid automatized naming. All significant at $p < .01$ (two-tailed).
* $p < .05$.

span and word span tasks as indicators of phonological short-term memory). The model fitted the data well, $\chi^2(130) = 216.320$, $p < .001$, CFI = .941, TLI = .930, RMSEA = .052, SRMR = .070.

The results of this regression are shown in Table 3. As can be seen, backward recall was important for both the learning phase ($\beta = .52$) and the retrieval phase ($\beta = .43$). However, the Wald test revealed that the regression weight on the learning phase was significantly higher, $\chi^2(1) = 9.144$, $p < .001$. In addition, Table 3 shows that phonological awareness was of importance for the learning phase (β = .36) and for the retrieval phase (β = .22), constraining parameters to be equal, Wald $\chi^2(1) = 8.877$, $p < .01$. At first glance, this also seemed to be true for RAN yet in the opposite way; a significant regression weight was found on the retrieval phase ($\beta = -.19$) but not on the learning phase ($\beta = -.04$). However, a closer analysis revealed that the regression weights were not significantly different, Wald $\chi^2(1)$ = 0.246, $p = .59$. No sufficient regression weights were found for the phonological short-term memory and for response inhibition (see Table 3).

Association of letter knowledge with PAL learning and retrieval

As can be seen in Table 2, significant correlations were found between all predictors. The correlation between the PAL learning and retrieval phases was high ($r = .86$), indicating that children who learned the new sound–symbol associations quite well made fewer mistakes in the retrieval phase. The correlation between the PAL learning phase and letter knowledge was .42, whereas the correlation between the PAL retrieval phase and letter knowledge was .49. The Wald's test suggested that this association was significantly different, $\chi^2(1) = 9.900$, $p < .001$.

Explaining variance in letter knowledge

To find out whether PAL mediates the relation of the cognitive predictors to letter knowledge, different structural models were calculated with letter knowledge as the dependent variable and PAL as a mediator of the different predictors. Fig. 2 shows the final structural model in which the PAL learning

Table 3
Standardized effects on the PAL learning and retrieval phases.

	Learning phase		Retrieval phase	
	B	*SE*	*B*	*SE*
Phonological awareness	.36**	.10	.22*	.03
RAN	−.04	.10	−.19*	.10
Backward recall	.52**	.13	.43**	.13
Phonological short-term memory	−.09	.10	−.14	.11
Response inhibition	−.09	.12	.06	.12
	$R^2 = .40$**		$R^2 = .44$**	

Note. PAL, paired associate learning; RAN, rapid automatized naming.
* $p < .05$.
** $p < .01$.

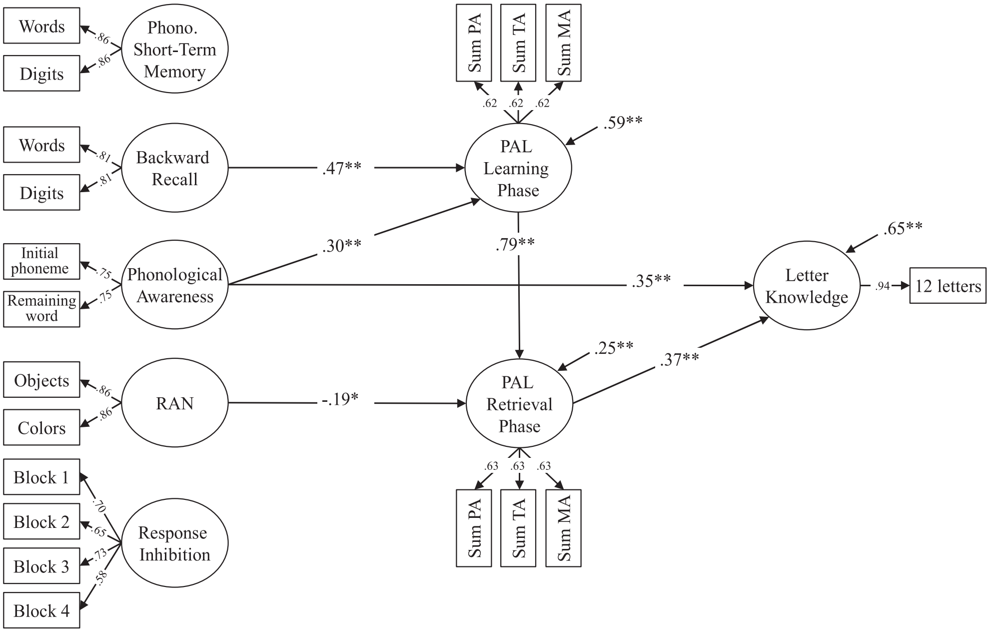

Fig. 2. Final structure model showing letter knowledge to be directly related to phonological awareness and the PAL retrieval phase (only significant paths are estimated). For the sake of clarity, the correlations between the exogenous measures and the correlation between the residuals of the PAL indicators are not depicted. $^{*}p < .05$; $^{**}p < .01$.

and retrieval phases were predicted by the five cognitive factors, whereas letter knowledge was predicted by the five cognitive factors as well as PAL. This model fitted the data well, $\chi^2(155) = 248.287$, $p < .001$, CFI = .938, TLI = .932, RMSEA = .050, SRMR = .070, and accounted for a substantial proportion of the variance of PAL learning ($R^2 = .41$), PAL retrieval phase ($R^2 = .76$), and letter knowledge ($R^2 = .35$). As depicted in Fig. 2, of the five cognitive predictors, only phonological awareness was uniquely related to letter knowledge ($\beta = .35$). Furthermore, the PAL retrieval phase accounted for a substantial proportion of the variance of letter knowledge ($\beta = .37$). Whereas a direct relation between the PAL learning phase and letter knowledge could not be found, a significant indirect relation via the PAL retrieval phase could be detected ($\beta = .28$; 95% CI = [.119, .444]). A small but significant relation could even be found via this connection (Backward Recall * PAL Learning * PAL Retrieval) for backward recall ($\beta = .13$; 95% CI = [.043, .232]) and phonological awareness (Phonological Awareness * PAL Learning * PAL Retrieval; $\beta = .08$; 95% CI = [.030, .178]). An indirect effect of RAN via PAL retrieval was not found ($\beta = -.07$; $p = .101$; 95% CI = [−.009, −.174]). Thus, the unique contribution of PAL on letter knowledge was $R^2 = .14$ (PAL letter knowledge coefficients minus the total indirect effect through PAL).

It should be noted that phonological awareness and backward recall were no longer directly related to the PAL retrieval phase when PAL retrieval phase was regressed by PAL learning phase (see Fig. 2). However, a significant indirect relation of backward recall via PAL learning phase was found ($\beta = .37$; 95% CI = [.216, .515]).

Discussion

The aim of the current study was to explore underlying factors of sound–symbol association skills. The results revealed a number of critical findings concerning the interrelationships among the association and retrieval of new sound–symbol correspondences, phonological awareness, RAN, backward recall, and letter knowledge. First, phonological awareness and backward recall are predominantly important when acquiring new sound–symbol pairs, whereas RAN, phonological awareness, and backward recall are of importance when new sound–symbol pairs need to be retrieved. Second, letter knowledge is more strongly associated with retrieval compared with learning of new sound–symbol pairs. Third, PAL abilities can be seen as mediators of associations between different reading precursor skills and letter knowledge.

Viewed descriptively, phonological awareness—that is, the ability to recognize, discriminate, and manipulate smaller units of spoken words—was found to be positively related to both PAL phases (learning phase $r = .50$, retrieval phase $r = .39$). The findings from the regression analyses suggest that phonological awareness is especially necessary when acquiring new sound–symbol pairs. This finding is in line with the results of previous studies demonstrating the close relationship between PAL tasks (with corrective feedback) and phonological awareness (e.g., de Jong, 2007; Mourgues et al., 2016; Windfuhr & Snowling, 2001). Moreover, the close relationship between phonological awareness and the acquisition of new sound–symbol pairs is plausible because PAL requires children to discriminate among different verbal stimuli (e.g., /ma/, /pa/, and /ta/ in the current study). However, the findings from the regression analyses further suggest that phonological awareness is less important when new sound–symbol pairs need to be retrieved. This is interesting because de Jong et al. (2000) showed that (a) phonological awareness and PAL performance in a task without corrective feedback are closely related and (b) training of phonological awareness improves visual–verbal performance in that task. At first glance, these findings are contradictory to our results. However, the performance in the PAL retrieval phase highly depends on the performance in the learning phase. This means that an improvement in the learning phase, where phonological awareness is of great importance, will enhance the performance in the retrieval phase. Moreover, in the current study, both PAL phases were considered in one regression analysis as dependent variables. Thus, it was possible to disentangle the relation between phonological awareness and the different PAL phases.

The regression analysis revealed that RAN affects less the learning but more the retrieval of new sound–symbol pairs. That is, the speed at which phonological information is retrieved from visual stimuli is important when sound–symbol associations need to be named without corrective feedback. By contrast, the correlation with RAN is smaller when the possibility is given to consolidate and/or correct sound–symbol associations, for example, based on corrective feedback or the presentation of the correct answer regardless of the accuracy of the response. This could explain why previous studies reported smaller correlations (Georgiou et al., 2017; Lervåg et al., 2009) or even no correlation between PAL abilities and RAN (e.g., Litt et al., 2013; Litt & Nation, 2014). Moreover, the fact that phonological awareness is more strongly associated with the PAL learning phase and RAN is more closely related to the PAL retrieval phase fits well with findings showing that phonological awareness is of particular importance at the beginning of reading acquisition, whereas RAN is considered to be of importance in the further course of reading acquisition, especially for retrieving words based on their graphic characteristics (orthographical processing; Frith, 1985).

Our results are in accordance with a broader body of evidence suggesting that working memory capacity is involved in the acquisition of novel phonological representations (Baddeley, 1996). More precisely, less the phonological short-term memory but rather the abilities of updating and manipulating (backward recall) proved to be of particular importance for performance in both the acquisition and retrieval phases of the PAL paradigm. The association between backward recall and performance in the acquisition phase might be due to the fact that the simultaneous acquisition of new sound–symbol pairs means that the sound–symbol pairs need to be simultaneously present in the mind. That is, when mapping a symbol to the associated sound, the other sound–symbol pairs need to be present to avoid incorrect associations. This task seems to involve backward recall rather than phonological short-term memory (Baddeley, 1996). However, the missing influence of phonological short-term memory can also be explained from a methodological perspective (which is directly related to an old problem regarding the assessment of updating and manipulating); namely, the shared variance of PAL abilities and phonological short-term memory might be captured by backward recall because repeating nonwords and digits in the reverse order requires children to have these sequences in mind in the given order.

Backward recall was also of importance for performance in the retrieval phase of the PAL paradigm. One possible explanation is that the sound–symbol associations were not yet automatically accessible due to the relatively short acquisition phase. Thus, whereas the relatively passive storage mechanism of phonological short-term memory does not seem to be sufficient for successful retrieval, backward recall might be necessary for actively retrieving newly learned sound–symbol associations (Miyake & Shah, 1999).

The results revealed that response inhibition is related to PAL abilities but does not explain any further variance in learning and retrieving sound–symbol associations when other factors are considered. One possible reason for the missing effect might be that there is no dominant response that needs to be inhibited in the PAL paradigm. For example, in contrast to classical response inhibition tasks, the current PAL task does not require children to react within a specified time frame. The fact that response inhibition does not explain any further variance is also likely due to backward recall measurement, capturing the shared variance of PAL abilities and response inhibition.

Considering the interplay and contribution of the different cognitive skills to letter knowledge, critical findings were revealed. First, performance in the retrieval phase of the PAL paradigm was found to be more strongly associated with letter knowledge than performance in the learning phase ($r = .49$ vs. $r = .42$). However, as can be seen in Table 2, the relations of the cognitive factors with PAL learning and letter knowledge are very similar (except backward recall) and differ from those with PAL retrieval. Moreover, also the comparison of the current results with findings of previous studies provides little clarity. For example, the correlations with letter knowledge for the learning and retrieval phases are higher compared with the correlation found by de Jong et al. (2000, $r = .34$; see also de Jong, 2007, $r = .25$ and $r = .24$) and are lower compared with findings from Lervåg et al. (2009, $r = .57$). Interestingly, de Jong et al. (2000) assessed PAL abilities without corrective feedback, whereas corrective feedback was given by Lervåg et al. (2009). Therefore, it is hard to conclude that learning and retrieving new sound–symbol associations are differentially related to letter knowledge and that whether corrective feedback is given or not has an impact on that association. Perhaps the time between the learning and retrieving phases is of greater importance and leads to differential effects. In the current study, the retrieval phase took place immediately after the learning phase.

Second, the PAL abilities can be seen as mediators between different cognitive factors and letter knowledge. A direct relation with letter knowledge was found only for phonological awareness, emphasizing the close relationship of these to skills (Burgess & Lonigan, 1998). The indirect effect of RAN on letter knowledge underlines the assumption of de Jong & Olson (2004), according to which the contribution of RAN to the acquisition of letter knowledge is due to PAL (more precisely, to the PAL retrieval phase). Moreover, the indirect effect of backward recall on letter knowledge via PAL also shows that these are involved in the acquisition of novel sound–symbol pairs but are not necessary for performance in letter knowledge tasks where lexical entries are built over a longer period of time (Baddeley, 1996; de Jong & Olson, 2004). Thus, different abilities are important for the three measures—PAL learning, PAL retrieval, and letter knowledge—which can be interpreted as three different stages of the acquisition of sound–symbol associations: learning phase of new associations, retrieval phase of new associations, and retrieval phase of associations from long-term memory, respectively. However, because a considerable amount of the variance of letter knowledge remains unexplained, the question arises as to which further abilities are related to letter knowledge.

Limitations and directions for further research

Several limitations of this study need to be considered. First, it is important to note that the data are correlational in nature. Thus, any causal interpretations, even though based on relevant theories, need to be treated with caution. To analyze effects of reading precursors on the different PAL phases and to test possible indirect effects on letter knowledge, longitudinal data are needed. In our study, we assumed directions of causality on the basis of previous studies suggesting (a) phonological awareness, RAN, and working memory to predict PAL (e.g., Mourgues et al., 2016), (b) PAL to display an early stage of acquiring letter knowledge (e.g., de Jong & Olson, 2004), and (c) PAL to mediate the relation between the different reading precursors and letter knowledge (e.g. de Jong & Olson, 2004).

Second, because the study focused on preliterate children, reading abilities could not be assessed. Thus, this study does not contribute to the question of the association between children's sound–symbol association skills and their reading skills. However, based on the results of the current study as well as previous studies, it is reasonable to assume that children's sound–symbol association skills are mainly the product of phonological awareness, backward recall, and RAN. Thus, when these capabilities and letter knowledge are regressed on word reading, an additional, direct, and unique contribution of PAL to word reading is expected to be small or even nonexistent (cf. Poulsen & Elbro, 2018). Therefore, future studies should assess a broader scope of reading precursors to clarify whether PAL is robust and independent not only from phoneme deletion and RAN (Litt et al., 2013) but also from backward recall and letter knowledge.

Third, PAL abilities were assessed for an age range in which the majority of children are familiar with at least some letters. In the current study, therefore, children with pronounced letter knowledge may have had an advantage in learning new sound–symbol pairs because these children are familiar with these kinds of associations. Thus, to more thoroughly analyze the implied causality of PAL predicting letter knowledge acquisition, PAL abilities should be assessed earlier in development or in samples of children without letter knowledge in longitudinal studies. Moreover, in the current study, no criterion was used to specify whether or not children learned the stimuli correctly. The retrieval phase started regardless of how well children learned the sound–symbol associations. Therefore, the retrieval phase can also be interpreted as a retention phase in which children have the opportunity to show what they have learned. In future studies, one possible indicator for the learning phase can be the number of trials necessary for learning the sound–symbol associations correctly in order to better differentiate between retrieval and retention.

Fourth, the question arises as to whether the PAL paradigm is suitable to simulate the acquisition and retrieval of letter knowledge. Whereas the simultaneous acquisition of several sound–symbol pairs requires pronounced backward recall abilities, it is reasonable to assume that the requirements are less pronounced in the actual educational context. Prior to school entry or in the first school year, wherever letters are introduced, they are presented separately, mostly in combination with words (e.g., "A like apple"), and repeated many times before new letters are introduced. That is, lexical entries of letters are built over a longer period of time, limiting the comparability to short experimental settings.

Conclusion

The empirical findings of this study present an important contribution to understanding the relation between PAL and different reading precursors. Our results shed new light on the requirements in the two PAL phases by disentangling the role of the different reading precursors. More specifically, phonological awareness and backward recall are predominantly important when acquiring new sound–symbol pairs, whereas RAN, phonological awareness, and backward recall are of importance when new sound–symbol pairs need to be retrieved. In addition, PAL proved to be mediating the relation between reading precursors and letter knowledge. Further longitudinal studies should take a possible mediation of PAL into consideration when investigating the contribution of the different precursors to reading.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jecp.2018.07.006.

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