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Reading Achievement in Relation to Phonological Coding and Awareness in Deaf Readers: A Meta-analysis

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The relation between reading ability and phonological coding and awareness (PCA) skills in individuals who are severely and profoundly deaf was investigated with a meta-analysis. From an initial set of 230 relevant publications, 57 studies were analyzed that experimentally tested PCA skills in 2,078 deaf participants. Half of the studies found statistically significant evidence for PCA skills and half did not. A subset of 25 studies also tested reading proficiency and showed a wide range of effect sizes. Overall PCA skills predicted 11% of the variance in reading proficiency in the deaf participants. Other possible modulating factors, such as task type and reading grade level, did not explain the remaining variance. In 7 studies where it was measured, language ability predicted 35% of the variance in reading proficiency. These meta-analytic results indicate that PCA skills are a low to moderate predictor of reading achievement in deaf individuals and that other factors, most notably language ability, have a greater influence on reading development, as has been found to be the case in the hearing population.

Learning to read at age-appropriate levels is a problem for many, but not all, students who are born deaf. Regardless of whether they speak or sign, the median reading level of deaf students indicates subpar achievement. Approximately 10% of deaf students read beyond an eighth grade level (Traxler, 2000). This statistic indicates that there are many skilled readers in the deaf population. The challenge is to discover what factors distinguish them from unskilled readers (Belanger, Baum, & Mayberry, 2010; Chamberlain & Mayberry, 2008). Only then can effective diagnostic and educational programs be devised to ameliorate the problem. Moreover, understanding the nature of proficient reading in individuals who are deaf promises to elucidate theoretical models of reading development and disabilities.

One candidate factor in need of better understanding is the role of phonology in reading. Alphabetic writing systems represent the phonology, or sound patterns, of spoken words to greater or lesser degrees. Much research has sought to discover the role phonology plays in the reading development of children who hear normally (National Reading Panel, 2000). Similarly, whether readers who are deaf use phonology in reading and whether their doing so is necessary to develop age-appropriate reading skills have been the subject of much research. In this article, we closely examine this body of work.

To investigate the role of phonology in the reading of deaf individuals, researchers have had to adapt paradigms originally designed for hearing individuals or create novel ones. Any review of the literature must thus carefully consider the diverse experimental approaches used in this line of inquiry, which is one aim of this article. The primary goal of this article is to conduct a meta-analysis of the existing research investigating this complex question. The advantage of a meta-analysis over a traditional narrative review is that it requires scrutiny of the methods and statistical results of each study in order to compute how much variance in one factor is explained by the variance of another factor, otherwise known as *effect size* (Rosenthal, 1984). In the present study, we computed

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the effect size of phonological coding and awareness (PCA) in relation to reading achievement in the deaf population. Before turning to the present study, we first describe how the terms *phonological coding* and *awareness* are used in this literature and return to the issue in the Methods section.

In an early set of studies, Conrad (1979) asked whether deaf children use phonology in reading. Based on his prior discovery that acoustic properties of speech are stored in short-term memory (Conrad, 1962), he attempted to quantify how much "innerspeech" deaf high school students could use by devising a metric called the *Inner-Speech Ratio.* The I-S ratio was the proportion of errors a student made when recalling written word lists that were homophonic (words in which the vowels rhyme but are spelled differently, e.g., *do* and *few*) over the sum of errors made on homophonic and nonhomophonic (e.g., *bare* and *bean*) lists combined. A high I-S ratio was interpreted to mean that the student used a cognitive form of mental representation that was speech based, otherwise known as the phonological similarity effect (Conrad & Hull, 1964).

It is important to note that the construct of phonological coding is an inference. Because errors are made remembering written words that sound alike, the conjecture is that the cognitive operations themselves manipulate some abstract attribute of speech. Important to this article is the fact that other codes are also used to maintain words in memory, such as orthographic (Logie, Della Salla, Wynn, & Baddeley, 2000) and semantic (Haarmann, Davelarr, & Usher, 2003). Subsequent studies followed Conrad's lead by employing variations of his paradigm to investigate whether deaf students can use phonological coding and whether their doing so predicts reading ability (Hanson, 1989; Lichtenstein, 1998; Waters & Doehring, 1990).

A recurring question in the literature is whether alternative means of sensory coding can be used by deaf children to develop speech-equivalent phonological coding skills. Some studies seek to determine whether lipreading skills can substitute for listening skills (Campbell & Wright, 1989). Other studies ask whether manual gestures for aspects of spoken phonology, such as Cued Speech or Visual Phonics, can facilitate development of phonological coding (Leybaert & Charlier, 1996; Narr, 2008). Note that the theoretical assumption underlying these types of studies is that phonological coding in some form is necessary for deaf children to read. Other studies seek to discover whether deaf students whose primary face-to-face language is signed, such as American Sign Language, Quebec Sign Language, or Sign Language of the Netherlands, show evidence of using phonological skills in word reading (Belanger et al., 2010; Chamberlain, 2002; Ormel, 2008). The theoretical assumption here is that the phonological representations associated with reading, because they are abstract (i.e., linguistic and cognitive), may be dissociated from sensory-motor modality and acquired as a consequence of reading development.

Many studies of normally hearing children have shown that training in phonological awareness facilitates early reading. A meta-analysis of this work found that 12% of the variance in word identification skills could be explained by such training in the short term; over the long term, less than 1% of the variance in reading was related to phonological awareness training (Bus & van Ijzendoorn, 1999). In contrast to phonological coding, phonological awareness is the knowledge that spoken words can be decomposed into subunits consisting of syllables, consonants, and vowels and the additional knowledge that letters represent these phonological units. Research with the hearing population has found that learning to read and phonological awareness skills are reciprocal. For example, reading facilitates the development of phonological awareness in English-speaking hearing children (Ehri & Wilce, 1980; Perfetti, Beck, Bell, & Hughes, 1987). Illiterate Portuguese adults who hear normally perform poorly on phonological awareness tasks compared to literate ones (Morais, Cary, Alegria, & Baertelson, 1979). Chinese hearing adults who speak Mandarin and read only characters perform poorly on phonological awareness tasks compared to those who read pinyin, a phonetic script (Read, Zhang, Nie, & Ding, 1986). The reciprocal nature of phonological awareness and learning to read is thought by some researchers to be an inherent confound in any study investigating whether training in phonological awareness improves reading development (Castles & Coltheart, 2004; Castles, Holmes, Neath, & Kinshita, 2003).

A perusal of studies investigating the relation of PCA to reading achievement in the deaf population reveals multiple conflicting results. For example, studies of deaf students who sign or speak have found evidence that they use phonological skills in reading (Colin, Magnan, Ecalle, & Leybaert, 2007; Harris & Moreno, 2004). Other studies of students who speak or sign have not found evidence (Dyer, Szczerbinski, MacSweeney, Green, & Campbell, 2003; Waters & Doehring, 1990). Such conflicting results suggest that PCA skills may not be the *sine qua non* of reading proficiency in the deaf population.

Reading disabilities in hearing children are incompletely understood and a number of theoretical models have been proposed to explain the role of PCA skills in reading development (McCardle, Scarborough, & Catts, 2001). In the *phonological core deficit* model of reading, impaired phonological skills (along with deficits in auditory processing and processing speed) are hypothesized to negatively affect both reading and language development (Liberman, Shankweiler, & Liberman, 1989; Tallal & Piercy, 1973; Wolf, Bowers, & Biddle, 2000). Other reading models hypothesize that language problems are a key factor in reading disabilities (Catts, Fey, Zhang, & Tomblin, 1999; Dickenson, McCabe, Anastasopoulos, Peisner-Feinberg, & Poe, 2003). In this framework, weak language skills are conjectured to cause difficulties in the domains of word recognition and reading comprehension. The two domains reflect different stages of reading development (Chall, 1983). Word recognition problems are identified earlier than reading comprehension problems, which cannot be detected until the student has acquired sufficient skill to read the text (McCardle et al., 2001).

Research investigating the relation of PCA skills to reading development in the deaf population can be used to inform these broader models of reading development. If PCA is the *sine qua non* of reading proficiency in the deaf population, this would provide evidence for the *phonological core deficit* model of reading development. However, if PCA inconsistently predicts reading achievement in the deaf population and if other factors are better predictors of reading achievement than PCA, then this would provide evidence for models of reading development that give a more prominent role to language abilities. In order to better understand the relation of PCA to reading achievement in the deaf population and to elucidate theoretical models of reading development, we undertook a meta-analysis of the available research.

Methods

The meta-analysis consisted of several steps: (a) locating the relevant studies; (b) determining whether the studies met inclusion criteria; (c) coding the experimental design and results of studies that met inclusion criteria; (d) categorizing the coded studies into two groups, studies that measured only PCA skills versus studies that additionally measured reading ability; (e) computing the total number of participants tested in the first group of studies (Bushman & Wang, 2009); (f) calculating the effect size for the second group (Rosenthal, 1984); and finally (g) identifying other factors that have been investigated in relation to reading proficiency in the included studies and computing effect sizes for these as well.

Data Collection

Databases. To locate all the available studies, we began with a thorough search of the following databases: CSA Linguistics and Language Behavior Abstracts, MLA International Bibliography, Eric and Sage databases, International bibliography of the social sciences, MedLine, PsycArticles & PsycInfo, and Google Scholar. A difficulty in collecting the relevant work comes from a lack, in this literature, of a unique and well-defined terminology.

Search terms. The terms *phonological coding/encoding/decoding/recoding* are often used interchangeably in the literature or used together but without clear distinctive definitions. This group of terms is generally used to refer to the orthographic-sound correspondence of written language and the application of this knowledge when reading or writing. The term *phonological awareness* is often used to specifically address the readers' knowledge of the *phonological units* of their language, but it has been treated by several authors as interchangeable with phonological coding (Harris & Beech, 1998; Luetke-Stahlman & Nielsen, 2003). However, phonological awareness is sometimes contrasted with *phonemic awareness*, which is generally defined as the ability to use knowledge gained from phonological awareness to manipulate those smaller units of sound, such as in the segmenting, substituting, and deleting tasks often found in standardized tests (Harris & Beech, 1998; Izzo, 2002; Luetke-Stahlman & Nielsen, 2003). Additional terminology used for similar phenomena include *phonological processing*, which has been used to refer to the use of phonological structure in memory (Wandel, 1989), and *epi-/meta-phonological processing*, which have been defined as "phonological sensitivity to linguistic units such as rimes, syllables, and phonemes" and "the ability to identify and manipulate the linguistic units in an intentional explicit way," respectively. The term *speech recoding* was used by Lichtenstein (1998) as "a process by which the reader transforms the printed information to some kind of speech-based code that may include auditory imagery." Finally, some authors do not use any of the above terminology, instead referring to the development of "abstract phonological representation" (Charlier & Leybaert, 2000), "sensitivity to the phonologic structure of words" (Hanson & McGarr, 1989), or "abstract phonological knowledge" (Olson & Nickerson, 2001).

In order to locate as many of the relevant papers as possible, we used all the relevant combinations of related search terms such as "*phonological/phonemic*" in combination with "*awareness/processing/coding*" etc. and filtered the results to include terms related to *deafness* and *reading*. We collected journal articles, conference proceedings, book chapters, and dissertations and did not consider unpublished work. A small number of included papers, missed in the database search, were found within reference lists of the relevant collected works; a smaller number of papers were obtained through personal communication with the cited authors. The data collection resulted in 231 total works. We cast a wide net for the sake of completion, although this meant much located research was not directly relevant. The next step, therefore, involved combing through the collected works to pinpoint all the relevant studies.

Inclusion Criteria and Coding

We devised an initial set of criteria for separating relevant analyzable studies from studies that were only marginally related to our research question or work that did not provide analyzable data, such as reviews of the literature or opinion pieces. First, we confirmed that each study investigated PCA skills, which we defined broadly as any experimental manipulation of the link between orthography and speech sound, phonological coding, or the ability to manipulate spoken phonemes, phonological awareness. Second, we confirmed that each study included a sample of deaf participants who were reported, by the authors of each study, to be severely or profoundly deaf (80 dB or higher in the better ear, although some studies explicitly included deaf participants with cochlear implants). The third inclusion criterion was that the study reported original data collected by the authors using experimental methods that were either clearly explained or evident from the data presentation. The fourth inclusion criterion was that the study reported either a complete summary of the raw data or the results of statistical analyses that tested the phonological coding or awareness effect.

Of the 231 collected works, 152 were eliminated based on the above criteria. Each of the remaining 79 studies was reviewed in detail. Key features of each study were examined and coded using a detailed protocol. Five coders (the authors and two additional researchers) practiced applying the protocol to a small set of studies. The coding protocol was adapted from those used in prior meta-analytic research (National Reading Panel, 2000; Wilson, 2009). The coded features for each study included the experimental paradigm of the data collection, the type of task used to measure PCA, the reading measures collected, the reported demographic information of the participants, the statistical analyses employed, and the results. All this information was maintained in a FileMaker Pro database. The coded study factors are given in Table 1. Coding reliability was established by having each coder independently recode two to three studies originally coded by another researcher.

Experimental PCA Tasks

Because PCA skills are postulated to either implicitly or explicitly reflect the mental association of speech sounds (phonology) with spelling (orthography) or the mental manipulation of spoken phonemes, valid measures of PCA skills must manipulate or examine these relationships and skills. In the second round of coding,

Table 1 Research study characteristics coded for meta-analysis

Research study feature
Year of publication
Experimental paradigm
List of dependent measures
Specific type of PCA measure
Statistical methodology
Analysis of variance
Comparisons
Correlation
Other
Reading measure
List of measures relating PCA to reading
List of additional measures predicting reading level
Stimuli description
Participants
Deaf participants
Preferred use of communication
Level of hearing loss
Hearing participants
Used as control
Means of comparison
Other participant features
Mean age or age range
Grade level

Note. PCA, phonological coding and awareness.

we found that some measures used in some of the remaining studies did not manipulate knowledge of sound subunits or the relation of sound to spelling and thus did not isolate PCA skills. For example, several studies used spelling proficiency as a dependent measure with the assumption that the factor determining spelling proficiency is phonological coding (Gates & Chase, 1926). PCA skills may play a role in spelling proficiency, but accuracy scores on a spelling test alone are not a PCA measure. Studies that used only a spelling proficiency task, without further analyzing spelling errors for their potential underlying sound-based motivations (e.g., misspelling the word “phone” as “fone” is phonologically motivated but misspelling it as “bhone” is orthographically motivated), were excluded. In the same vein, some studies measured participants’ familiarity with orthographic patterns without reference to phonology, which also does not isolate PCA skills. For example, Hanson (1986) tested deaf subjects’ sensitivity to orthographic structure by using perceptual and judgment tasks with letter strings that varied in their degree of orthographic regularity.

Several other studies incorporated measures that do not clearly control for participants’ use of alternative nonphonological strategies. For example, in one study, participants’ knowledge of syllable structure was assumed to result from phonological input (Transler, Leybaert, & Gombert, 1999). However, syllabic structure can also be deduced via statistical patterns based on orthographic familiarity. Simple knowledge of frequency differences between vowels and consonants could lead to the effects measured in this study. In such tasks, deaf participants who are avid readers are more likely than casual readers to deduce knowledge of syllabic structure irrespective of potential PCA skill. Another example was studies that made use of a “treatment package” that involved the explicit instruction of phonological patterns of spoken language (Trezek & Malmgren, 2005). These studies tested the ability to retain PCA skills rather than testing the degree to which the deaf participants used PCA skills to read words. Altogether 26 studies were eliminated due to the fact that the experimental design did not single out the effect of PCA skills, which may or may not have been the intent of the study, resulting in a final set of 57 studies. Appendix A gives the 22 excluded studies.

Study Data Set

The final set of 57 analyzable studies was conducted in several countries, including the United States, the United Kingdom, Canada, Germany, Belgium, France, the Netherlands, and Israel. Combined, the studies tested 2,078 deaf participants ranging in age from 4 to 62 years. In each study, participants were typically reported as being proficient in varying communication modalities and languages, such as a sign language, sign supported speech, cued speech, speech, or a combination. The experimental designs of these 57 studies were analyzed in detail and recoded for every experimental aspect of each study. Appendix B gives the 57 studies included in the count.

Results

The 57 studies yielded three categories of effects: (a) studies finding evidence that the deaf participants used PCA skills; (b) studies failing to find evidence that the

Table 2 Vote count of the number of studies (and no. of participants) finding significant effects for PCA skills in full and subgroup analyses

	Evidence for PCA skills	
Study participant sample	Yes	No
Full group analyses	16 (515)	20 (536)
Subgroup analyses	11 (223)	11 (273)

Note. PCA = phonological coding and awareness.

deaf participants used PCA skills; and (c) studies finding evidence for PCA use but only in a subset of the participants tested or a subset of the tasks[1]. Table 2 shows these results.

PCA Effect by Vote Count

The first set of results (see Table 2) indicates that some level of PCA use is present in some individuals in the deaf population, although nearly half of the studies conducted did not show a statistically significant effect of PCA use by the participants. It is important to note that categorizing a study as either showing evidence (statistically significant effects) or not showing evidence of PCA (nonsignificant effect) does not indicate that each study participant performed uniformly on the PCA tasks. Rather, a study is counted as showing evidence for PCA if the group mean performance (averaged across participants) reaches statistical significance.

The finding that PCA is present in roughly half the studies analyzed and that approximately half of the studies did not find significant effects suggests that PCA is not a robust phenomenon in individuals with severe and profound hearing loss. A possible reason for the result is that the experimental measures of some of the studies may not have been sensitive to the PCA strategies used by this population. Also, for the studies that did not find evidence, some number of their participants may have used some measurable PCA skills. However, the reverse situation is also true. An equal number of participants in the studies who found evidence for PCA skills may not have exhibited those skills. Therefore, another reason for this evenly split vote count could be that a large portion of the deaf population might not, or cannot, make use of PCA strategies.

Do PCA Skills Reliably Predict Reading Proficiency?

The results of the vote count of PCA effects in the extant literature indicate that it is possible to find evidence of PCA skills in deaf readers. However, the crucial question is whether PCA skills predict reading proficiency. To answer the question, we analyzed the subset of identified studies that included a statistical measure of the relation between PCA and reading skills.

Of the 57 studies employing a valid measure of PCA skills in a sample of deaf participants, 25 also measured the participants' reading ability and calculated a statistic assessing the degree of relation between PCA and reading, such as a correlation or a multiple regression. These 25 studies are listed in Table 3.

Effect size. For each of the 25 studies, we identified the correlation between the measured PCA skills and reading ability. We used r as the effect size measure across the studies. Importantly, effect sizes reported as r scores do not indicate a causal relationship between PCA and reading. Rather, this statistic indicates that PCA scores are mathematically predictive of reading scores across participants in a given study. The correlation shows the amount of variation in reading proficiency that is shared with PCA skills.

Next, we converted each r to a single z score to represent the quantitative relationship between PCA and reading skills found by each study. This z score is a logarithmic transformation of the correlation statistic r, using the following formula:

$$z_r = \frac{1}{2}\ln\left[\frac{1+r}{1-r}\right]$$

In the formula, r is the correlation between the PCA measure and the reading measure and ln is the natural log. The rationale for transforming each study's correlation to a z score is to control for the skewing that occurs when a sample includes a large range of correlations. Here, the sample is the research studies. The z transformation serves to reduce skewing in the sample, thereby increasing the validity of computations on the sample's effect sizes, such as the mean

Table 3 Effect sizes of studies included in analysis of phonological coding and awareness skills and reading proficiency

Authors	*N*	Language	Mean age	Age range	Task	Reading test	Effect size
Chamberlain (2002)	29	English	37.0		Lexical decision with pseudohomophones	Stanford 9 (Psychological Corporation, 1995)—reading comprehension subtest; Gates-MacGinitie Reading Tests, 2nd Canadian Edition (MacGinitie & MacGinitie, 1992)—comprehension subtest	−0.13
Transler and Reitsma (2005)	48	Dutch	9.7	6.7–13.4	Lexical decision with pseudohomophones	Schaal Betekenisrelaties; Schaal Verwijsrelaties (CITO, 1992)—reading comprehension	−0.07
Beech and Harris (1997)	36	English	9.8	6.6–12.2	Lexical decision with pseudohomophones	British Ability Scales single word reading test (Elliot, Murray, & Pearson, 1983)	0
Hanson and Fowler (1987)	12	English	20.0	18–22	Lexical decision—word pairs (rhyming, pseudohomophones)	Gates-MacGinitie Reading Test (1969, Survey F, Form 2)—comprehension subtest	0
Olson and Nickerson (2001)	20	English	18.0	17–19	Letter identification at/within syllable boundaries	Stanford Achievement Test—reading comprehension	0.04
Gibbs (1989)	19	English	17.4	16–19	Letter cancellation	Gates-MacGinitie (MacGinitie, 1978) comprehension test; Stanford Achievement Test (Madden, Gardner, Rudman, Karlsen, & Merwin, 1973)—reading comprehension subtest	0.05
Izzo (2002)	29	English	9.3	4.3–13.4	Picture matching (phoneme and rhyme)	Story Retelling task, scored from 1.0 to 10.0	0.09
Charlier and Leybaert (2000)	40	French	16.8		Rhyme generation	Lobrot Test (cloze procedure; Lobrot, 1973)	0.23
Waters and Doehring (1990)	56	English	13.54	7–20	Word recall—rhyming vs. nonrhyming	Stanford Achievement Test—Hearing Impaired—paragraph meaning subtest	0.24
Weaver-Trumble (1996)	26	English	13.0	16–19	Word recall; rhyme generation; rhyme judgment	Peabody Individual Achievement Test (Markwardt, 1989) reading comprehension subtest	0.28
Kyle and Harris (2006)	29	English	7.8	6.7–8.6	Picture matching—phoneme	Primary Reading Test—sentence comprehension (France, 1981)	0.32

Table 3 Continued

Authors	*N*	Language	Mean age	Age range	Task	Reading test	Effect size
Hanson and McGarr (1989)	15	English	25.0		Rhyme generation	Gates-MacGinitie Reading Test (1969, Survey F, Form 2)—comprehension subtest	0.34
Harris and Beech (1998)	24	English	5.0	4–6	Picture matching—phonemes	Primary Reading Test Level 1A—single word recognition	0.42
Geers (2003)	181	English	9.5	8.0–9.9	Lexical decision with pseudohomophones; rhyme judgment	Peabody Individual Achievement Test-Revised (Dunn & Markwardt, 1989)—reading comprehension subtest	0.43
Colin and colleagues (2007)	21	French	6.17	5.4–7.3	Picture matching—rhyme and phoneme; rhyme generation	Written word choice test (Ecalle, 2003)	0.45
Dyer and colleagues (2003)	49	English	12.7		Picture–picture or picture–pseudohomophone rhyme matching	National Foundation for Educational Research Group Reading Test—cloze procedure	0.45
Campbell and Wright (1988)	32	English	14.7	11.3–16.7	Rhyme judgment	Neale Analysis of Reading Ability	0.46
Lichtenstein (1998)	86	English	20.8		Word recall—rhyming vs. nonrhyming	California Achievement Tests Battery, Junior High Level (Tiegs & Clark, 1963)—Reading Comprehension subtest	0.48
Wandel (1989)	90	English	10.8	7–16	Word recall—rhyming vs. nonrhyming	SAT reading comprehension	0.57
LaSasso and colleagues (2003)	20	English	20.3	16–26	Rhyme generation	SAT-9 Reading Comprehension	0.59
Spencer (2006)	29	English	11.75	7.2–17.7	Elision (phoneme deletion)	Woodcock Reading Mastery Test (Woodcock, 1987)—passage comprehension test cloze procedure	0.60
Harris and Moreno (2004)	62	English	11.3	7–14	Spelling task—phonological errors	British Abilities Scales II Single Word Reading Test (Elliott, Smith, & McCulloch, 1996)	0.61
Ormel (2008)	62	Dutch	9.0		Picture matching—rhyme	Leestechniek & Leestempo (Krom, 2001)—cloze procedure	0.64
Harris and Moreno (2006)	18	English	8.0	7–8	Spelling test—phonological errors	British Abilities Scales II Single Word Reading Test (Elliott, Smith, & McCulloch, 1996)	0.72
Luetke-Stahlman and Nielsen (2003)	31	English	12.0	7–17	Segment syllables, manipulate sounds, blend syllables, and phonemes	Woodcock Reading Mastery Test (Woodcock, 1998)—passage comprehension subtest	0.86

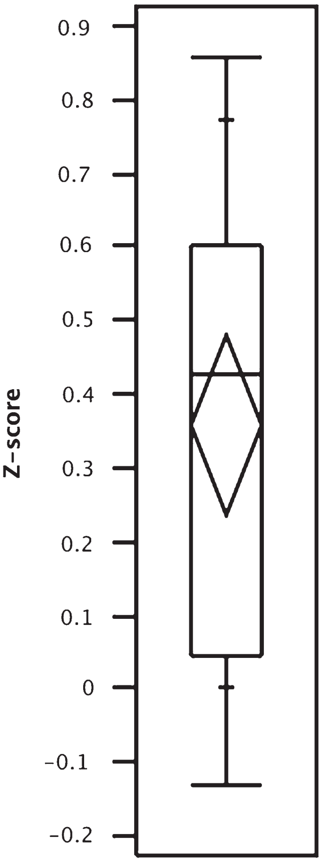

Figure 1 Box plot showing the mean (0.35), median (0.42), and quartiles of effect sizes of analyzed studies.

and standard deviation, as explained by Rosenthal (1994):

> One of the most important effect size estimates in meta-analytic work is *r*. However, as the population value of *r* gets further and further from 0, the distribution of *r*'s sampled from that population becomes more and more skewed. This fact complicates the comparison and combination of *r*'s, a complication addressed by Fischer (1928) …. In virtually all meta-analytic procedures, whenever we are interested in *r*, we actually carry out most of our comparisons not on *r* but on its transformation *z* (p. 240).

Mean effect size. To quantify the relationship between PCA and reading skills across the studies, we computed the mean effect size of the studies using the *z* scores. The results showed the mean *z* of 0.35, with a standard deviation of 0.27, and a 95% confidence interval ranging from 0.24 to 0.45, as Figure 1 shows. The mean *z* score represents an r^2 of .109, indicating that on average 11% of the variance in reading achievement in the deaf population can be explained by PCA. To better understand the overall mean effect size, it is necessary to elucidate how we obtained individual *z* scores from the data available in each study.

Single correlation reported. Some studies (Hanson & McGarr, 1989; Izzo, 2002; Kyle & Harris, 2006; LaSasso, Crain, & Leybaert, 2003; Lichtenstein, 1998; Olson & Nickerson, 2001; Spencer, 2006; Transler & Reitsma, 2005) reported a single correlation between PCA and reading. In such cases, the *r* value was taken directly from the study and converted to a *z* score.

Multiple correlations reported. Some studies reported more than one correlation between PCA and reading. For example, some studies used several different tasks to assess PCA skills (Campbell & Wright, 1988; Dyer et al., 2003; Geers, 2003; Luetke-Stahlman & Nielsen, 2003), and performance on each of task was correlated with a single reading score yielding several correlations. In other studies, participants were divided into subgroups based on particular demographic characteristics, such primary communication mode (Wandel, 1989) or age (Waters & Doehring, 1990). Other sources of multiple correlations included studies with more than one reading comprehension measure (Chamberlain, 2002; Gibbs, 1989), studies that measured reading achievement at two different time periods (Harris & Beech, 1998; Ormel, 2008), and combinations of the above (Weaver-Trumble, 1996). In all studies reporting multiple correlations, for the purposes of discovering our main effect size, we converted each reported correlation into a *z* score and then computed a mean of that study's *z* scores to arrive at a single, *z* score. This procedure ensured that each study contributed one effect size to our meta-analysis (Rosenthal, 1984). In the post hoc analyses of tasks and stimuli described below, we retained the multiple effect sizes from single studies.

Relationship reported as a regression. In cases in which the relationship between PCA and reading was presented as part of a multiple regression analysis (Colin et al., 2007; Harris & Moreno, 2004, 2006), we first obtained the r^2 value for the specific step in the regression that addressed PCA and then converted this to r, from which we calculated the z score.

Missing data. In three cases (Beech & Harris, 1997; Charlier & Leybaert, 2000; Hanson & Fowler, 1987), the authors reported that they attempted a correlation between the PCA and reading measures and found the relationship to be nonsignificant. However, they did not report r scores or p values. In a fourth case (Waters & Doehring, 1990), the authors reported r scores only for the significant correlations. In these four cases, given a relationship that was not statistically significant, we assigned an r value of 0. This is an accepted practice for when missing data points are believed to be small values (Pigott, 2009).

In order to explore the possibility that replacing these missing correlations with a value of 0 produced an underestimation of the overall effect size, we recalculated the overall mean two alternative ways. First, using the number of study participants and an assumed p level of .05 for all the missing values, we obtained an overall mean z score across the studies of 0.40. Second, we repeated the calculation using an assumed p level of .1 for all missing values and again obtained an overall mean of 0.40. Thus, using an approach that assumes an r value greater than 0, with levels of either minimal significance ($p = .05$) or nonsignificance ($p = .10$), increases the overall mean by a margin of 0.05. Given that this margin is well within the standard deviation and confidence interval of the originally calculated overall mean, we proceeded with the remaining calculations by replacing missing r values with 0 to obtain an overall mean of 0.35.

Weighted mean. The number of participants tested in each study ranged from 8 to 181. Given this large range, we recalculated the overall mean by weighting each z score based on the number of participants contributing to each correlation (Hedges & Olkin, 1985). That is, the effect size from studies with a large number of participants was given more leverage in calculating an overall mean than the effect size from studies with a small number of participants. Recalculating each effect size using this process, we obtained a mean weighted effect size of 0.43. This mean is 0.08 higher than the overall mean but remains within the confidence interval. Furthermore, given the heterogeneity of participant characteristics and type of tasks involved across the studies, assigning a greater value to those studies that involved a larger number of participants might give a disproportionate amount of weight to a particular type of participant or task. For example, Geers (2003) tested 181 deaf readers, all of whom had cochlear implants[2]. This subpopulation of deaf readers with cochlear implants may not represent the larger population of deaf individuals but the mean z score of 0.41 would be more heavily weighted than a study with far fewer participants. Thus, all further calculations were based on a nonweighted mean, which more accurately represents the wide range of characteristics observed in both the participants and the tasks.

Variance in effect size. The overall mean of 0.35 represents a large range of z scores collected from all the studies, from a low of −0.13 to a high of 0.86. The range and distribution of effect sizes is shown in the stem and leaf plot in Figure 2.

The large and nonnormally distributed range of effect sizes indicates that the relationship between

Levels of effect size

.8	6
.7	2
.6	0,1,4
.5	7,9
.4	2,3,5,5,6,8
.3	2,4
.2	3,4,8
.1	
.0	0,0,4,5,9
-.0	7
-.1	3

Figure 2 Stem and leaf plot of effect sizes of analyzed studies.

Table 4 Effect size for phonological coding and awareness–reading relationship as a function of cognitive task requirements and unit of spelling–sound manipulation employed in the analyzed studies

	Spelling–sound unit of manipulation						
Cognitive task	Syllable	Phoneme	Rhyme	Pseudohomophone	Regular	Spelling	Silent letter
Memory			0.43 (4)				
Identification	0.04 (1)	0.09 (1)					0.05 (1)
Matching		0.37 (2)	0.53 (2)	0.50 (1)			
Judgment			0.36 (5)	0.05 (5)	0.00 (1)		
Produce writing			0.37 (4)			0.67 (2)	
Produce speech	0.91 (1)	0.64 (3)					

Note. Mean effect size of cell studies (no. of studies contributing to cell mean).

PCA and reading is inconsistent across studies, suggesting that effect size is modulated by other factors. In the following analyses, we identified and examined the factors most likely to contribute to variation in effect size. Specifically, we computed effect sizes associated with the particular PCA tasks employed by the studies and the reading levels of the study participants.

Other Factors Modulating Effect Size

PCA task. Tasks created to deduce the level of PCA used by hearing participants often require the use of audition and speech, both to comprehend the task and to produce the response, which is the dependent variable. Although these tasks are sometimes used without modification, the fact that deaf readers have limited or no auditory access presents an obvious confound in evaluating performance. Thus, researchers have developed a set of tasks that are designed to assess PCA skills in deaf readers without the use of auditory presentation or vocal response. One consequence of modifying or creating de novo each PCA task is that it becomes difficult to compare the results of multiple studies. For example, it would not have been meaningful to group all studies using rhyme to assess PCA into a single category due to the variation in how rhyme was assessed (e.g., in memory tasks, judgment tasks, lexical decision tasks, etc.). Our analysis reveals that the PCA tasks used across studies vary widely with respect to both the cognitive demands asked of participants and the specific spelling–sound manipulations used to assess PCA skills.

In order to better understand how PCA tasks affected overall effect size, we categorized each study in the meta-analysis in a matrix using task requirements as one factor and the unit of spelling–sound manipulation as the second factor. By analyzing each task according to these two factors, we were able to identify experimental commonalities across studies. Because our focus of interest in this subanalysis is the relation of cognitive task type and spelling–sound unit on effect size, we used all the correlations reported in studies that reported them. This means that more effect sizes are given in Table 4 than were given in the previous analysis in which each study contributed only one effect size, as is standard practice in meta-analytic work (Rosenthal, 2000). The result of this post hoc analysis (which includes each study in the previous analysis) contains six levels of PCA cognitive task requirement and seven levels of spelling–sound manipulation (Table 4). The rows show all the levels of task, and the columns show the spelling–sound manipulations, used in the analyzed studies. The empty cells indicate that not all combinations of cognitive task and spelling–sound manipulation were represented by the analyzed studies. Each category is explained below.

Cognitive requirements. The cognitive requirement of a task is defined as the specific demand placed on the deaf participant in performing the task and consisted of the following six possibilities:

1. Memory: Memory tasks require the participant to recall and then either recognize or reproduce a set of phonemes, letters, words, or nonwords, presented as either individual items or as a list.
2. Identification: These tasks require the participant, when given a set of items (e.g., words or pictures), to identify two items that share

a specific property (e.g., initial phoneme, rhyme) or one item of several that does not share the property.

3. Matching: In matching tasks, the participant is given a target item and then asked to choose one or more items that match the target. These tasks are quite similar to identification tasks, with the addition of a specific target item.
4. Judgment: These tasks require participants to make a categorical judgment about one or more items with regard to a variety of factors (e.g., rhyming/nonrhyming, word/nonword, item belonging to a category).
5. Production in writing: These tasks require the participant to provide a written response (e.g., writing letters, words)
6. Production in speech: These tasks require the participant to provide a vocal response and represent tasks that are not modified from their original design as tests for hearing readers.

Spelling–sound relationship. Studies also tested PCA skills by manipulating the spelling–sound relationship of the stimuli at any of the following levels:

1. Syllable: These tasks require the participant to divide a word according to syllable boundaries (in speech or writing). Alternatively, some tasks require the participant to identify a letter or a property of a letter (e.g., color) in which case the experimental manipulation involves the placement of the letter either within or at a syllable boundary.
2. Phoneme: These tasks involve phoneme manipulation either in isolation or contained within a word and typically require the participant to identify, at the word level, items with common phonemes in a particular position (e.g., initial, medial, final).
3. Rhyme: This is a common manipulation of spelling–sound relationships. Rhyme can be used in multiple ways, but two are most common. The first type requires the participant to recognize rhyming words from a set or produce rhyming words in writing. The second type requires the participant to memorize sets of letters or words in which at least one set consists of items that rhyme.
4. Pseudohomophone: A pseudohomophone is a nonword that is a homophone of a real word. Pseudohomophone tasks typically require the participant to make a lexical decision about whether a word is real, with the assumption that if the participant is relying on phonology to read the word, there will be more errors and/or a slower response time on pseudohomophones relative to other nonwords.
5. Regularity: Tasks that use spelling–sound regularity categories as a manipulation (e.g., the sound/u/is generally considered to be an irregularly spelled sound as it corresponds to various spellings: *food*, *blue*, *fruit*, *to*. Conversely, the sound/i/is spelled with a double ‘e’ with high frequency and is therefore considered regular) assess the participants’ sensitivity to the varying categories of spelling and sound rules used in English.
6. Spelling: Spelling tasks require the participant to produce written words; spelling is then analyzed according to the phonological integrity of the spelling errors.
7. Silent letters*:* These tasks require the participant to identify a specific letter within a passage; accuracy on letters that are pronounced versus those that are “silent” (e.g., the letter “e” in “kite”) is compared.

In addition to cognitive requirements and spelling–sound manipulations, the study tasks varied as to whether they tested phonological awareness, coding, or both. Tests designed to assess phonological awareness use only pictures or vocal presentation and contain no use of orthography. Measures designed to test phonological coding involve written language at the letter, syllable, or word level.

Effect Size by Cognitive Task and Spelling–Sound Manipulation

We entered the number of studies using each combination of cognitive task and spelling–sound manipulation in the table. This revealed that some experimental constructs were used across several studies; some possible combinations of task requirements and spelling–sound correspondence were used in a single study; and many possible combinations were never used (see Table 4). The analysis shows that the most common cognitive requirement used across the studies involved judgment tasks, where participants make decisions about whether presented items are real words or not, whether items rhyme or not, or whether sets of pictures represent objects with names sharing particular phonological features. This analysis further shows that the most common spelling–sound manipulation involves the use of rhyme, either as a dependent variable in sets of stimuli or as a feature of the required response.

Effect size by task. Next, we plotted the effect size for each cell in the matrix; that is, for each experiment or set of experiments that used a particular combination of task and spelling–sound manipulation, we calculated the mean relationship between PCA and reading. The mean effect size for any given task and spelling–sound manipulation ranged from 0 to 0.91. Note again that for the current analysis, the studies were broken down into subtasks and plotted in Table 4. For this reason, this current range does not use precisely the same effect sizes as were included in the overall mean effect sizes reported in the previous analysis.

Plotting each effect size as a function of task and spelling–sound manipulation yields several additional findings. Studies that used tasks requiring auditory presentation and vocal response were likely to produce a high correlation between PCA skills and reading ability. The tasks in these studies were taken from standardized tests of phonological processing designed for use with hearing populations. Spencer (2006) used the Elision subtest from the Comprehensive Test of Phonological Processing (Wagner, Rogesen, & Rashotte, 2001). Luetke-Stahlman and Nielsen (2003) used subtests from the Test of Phonological Awareness (Torgesen & Bryant, 1994) and the Phonological Awareness Test (Roberson & Slatter, 1997). In the elision subtest, the experimenter says a word and then the participant is required to delete a sound from that word and produce the resulting word. For example, the experimenter could ask the participant to "Say 'trail,' without the 'r,'" and the participant is required to produce the response "tail." In a blending words task, participants may be asked, "What words do these sounds make?" followed by the test stimulus "can dee," and the correct response for such an item would be the word "candy." This kind of task is therefore highly reliant on hearing, lipreading, and speech skills.

The most common spelling–sound manipulation involved tasks that used rhyme. The mean effect size for these tasks was 0.39, which is very close to the overall mean of 0.35. The rationale for experimental constructs using rhyme is that readers must rely on phonology to some degree in order to either identify items that rhyme or generate rhymes on their own. Furthermore, tasks can be administered to deaf readers without reliance on audition or speech. However, in describing their procedure, Dyer and colleagues (2003) point out that "many deaf participants were unfamiliar with the concept of rhyme . . . this was explained to them and discussed at length using examples" (p. 220). Thus, interpretation of rhyme tasks must take into account the potential for orthographic confounds and deaf readers' possible lack of familiarity with the rhyme concept.

At least five studies in the meta-analysis assessed phonological coding using experimental designs that included pseudohomophones. In these tasks, participants are asked to determine whether a sequence of letters represents a real word or not or decide the semantic category of a stimulus. For example, Chamberlain (2002) presented participants with nonwords, such as "baik, durt, fome, joak, and paije," which when pronounced are homophonic to the real words "bake, dirt, foam, joke, and page," and contrasted lexical decision speed and accuracy on these stimuli to nonwords, such as "croob, flefe, purst, and staim," which have no real word counterpart. The rationale is that participants who are using phonological coding in word recognition will be slower and less accurate in rejecting the pseudohomophones as nonwords in comparison to nonwords that are not pseudohomophones.

Notably, of all the cells in Table 4 of task type that included more than one study, the five studies that relied on pseudohomophone-based tasks produced the smallest mean effect size (mean $z = 0.05$). This includes three studies (Geers, 2003; Hanson & Fowler, 1987; Transler & Reitsma, 2005) in which deaf readers showed significant evidence of phonological coding on other tasks and two studies (Beech & Harris, 1997; Chamberlain, 2002) where deaf readers showed no evidence of phonological coding. Regardless of the participants' phonological coding abilities, across all but one study, there was no significant correlation between that ability and reading ability. This result indicates that, in tasks where the possibility of using orthographic strategy in word recognition is more closely controlled, phonological coding ability (whether it is present or absent) is not predicting reading ability.

Despite the patterns we observed, there remains a significant amount of variance in effect size that cannot be accounted for by task characteristics. This means that other factors are modulating effect size. We turn next to the factor of reading level.

Effect Size in Relation to Reading Level

In order to determine when PCA skills are important to the reading development of hearing readers (e.g., beginning vs. advanced readers), researchers have examined the chronological age of the participants. However, given the substantial range of reading abilities among deaf readers, chronological age and reading age often show large discrepancies. We culled information about the reading grade level of the participants in the studies in order to detect trends in the contribution of PCA skills to the reading abilities of deaf students at various levels of reading development.

In 21 of the 25 studies, some information was provided regarding participants' reading abilities, either as part of the description of background characteristics or as part of the experimental study itself. We obtained a mean reading grade level for each of these studies. In cases where a mean reading grade level was reported, no further manipulation was required. In cases where a mean reading age was reported, we obtained an equivalent grade reading level by applying the following formula: reading grade = (reading age − 5), such that a 10-year-old reading level became a fifth grade reading level. In a subset of studies, reading ability was reported as a mean score on a standardized test. In these cases, we converted the deaf readers' scores to a mean reading grade level by consulting the norms available from the standardized tests. In still other studies, reading level was reported only as a range in which cases we calculated the median from that range[3]. Finally, in two studies (Harris & Moreno, 2004; Waters & Doehring, 1990), participants were grouped by chronological age and reading age and correlations were provided for each age group. In these two cases, we computed reading age and effect size for each chronological age group in the study.

We analyzed the relation of effect size to the reading level reported for each study. There was no apparent relationship between reading level and effect size, $r^2 = .037$. The range of effect sizes in deaf readers was large at every reading grade level, as Figure 3 shows. In beginning readers, that is, either prereaders or those reading below the second grade level, the mean effect size across four groups was 0.45, with a range of 0.32–0.59. In proficient readers, that is, those reading at or above the eighth grade level, the mean effect size across four groups was 0.36, with a range of 0–0.59. In sum, reading level did not account for any of the variation in effect size.

Additional Factors Predicting Reading Level

Our meta-analysis found a small to medium overall effect size of 0.35 for the relationship between PCA and reading in deaf readers, accounting for approximately 11% of the variance in reading ability. Given the large range of reading ability among deaf readers, we are left with the problem of identifying what factors account for the remaining 89% of the variance. In order to fully address this question, it would be necessary to do a comprehensive review of the literature examining all possible factors contributing to reading ability in the deaf population. Although such a review is beyond the scope of this article, we were able to look within the studies included in the meta-analysis. We included any variables that were assessed and correlated with reading ability in a minimum of two studies. This analysis yielded nine additional factors that were statistically measured in the studies with respect to their relationship to the reading proficiency of the deaf participants, as Table 5 shows.

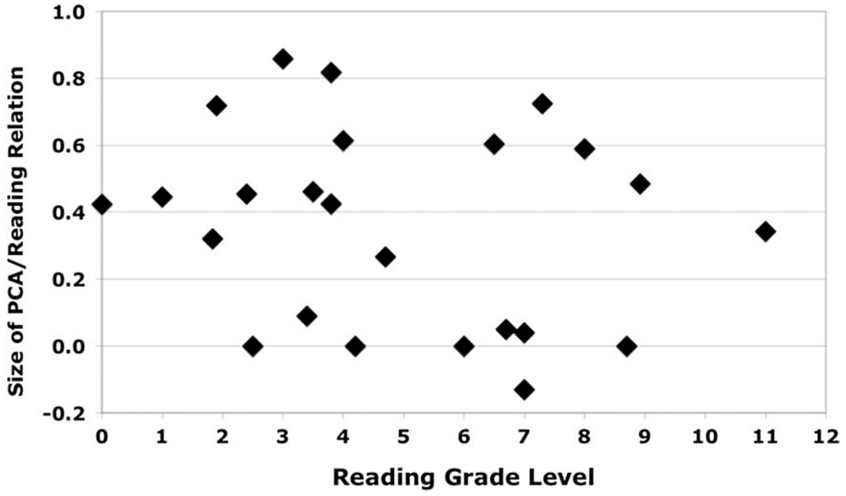

Figure 3 Phonological coding and awareness (PCA) effect sizes for the analyzed studies as a function of mean reading grade level in 21 studies that provided reading level data (including separate data points for three studies that provided correlations for multiple reading-level groups).

This analysis revealed a range of effect sizes (reported here as mean *r* values) for these nine additional factors. Several factors, namely, speech intelligibility, speech reading, nonverbal IQ, memory span, and orthographic knowledge, predicted roughly the same amount of variance in reading ability as did PCA skills. Chronological age and fingerspelling predicted less variance, whereas hearing ability predicted a greater amount of variance but still within 1 *SD* of the overall effect size for PCA skills.

Across seven studies, language ability predicted a greater amount of variance than any other factor. Language ability predicted, on average, 35% of the variance in reading ability, with *r* values ranging from .32 to .86. Language was measured using a wide range of assessments, including both spoken and signed vocabulary production and comprehension measures (measures that relied on written word recognition or spelling ability were not included in this correlation, as these measures incorporate reading ability to some degree). In sum, in the studies that measured PCA skills and reading proficiency in addition to other factors, language ability emerged as the factor most highly correlated with reading ability in deaf readers.

Table 5 Additional factors correlating with reading ability

Factor	No. of studies	*r*	*SD*
Phonological coding	25	.34	0.23
Language ability	8	.59	0.20
Hearing level	3	.44	0.24
Speech intelligibility	7	.36	0.25
Nonverbal IQ	13	.37	0.20
Memory span	5	.36	0.17
Speechreading	7	.32	0.23
Age	11	.24	0.24
Fingerspelling	2	.18	0.40

Discussion

Using the available research, we performed a meta-analysis to determine the degree to which PCA skills explain reading proficiency in the deaf population. If PCA skills are necessary for deaf individuals to develop proficient reading, the prediction is that these skills will consistently and highly relate to reading ability across the studies. However, if PCA skills are one factor among others affecting reading proficiency, the prediction is that they will inconsistently predict reading ability across the studies. The meta-analytic results fit the second prediction. PCA skills are not the *sine qua non* of reading proficiency in the deaf population. These results are inconsistent with the *phonological core deficit* model of reading disabilities, one of several explanations proposed to explain reading development and disabilities in hearing children (McCardle et al., 2001). Evidence for this finding took several forms in the meta-analysis results. Here, we discuss these results in light of the overall effect size, the experimental complexity inherent to this line of work, the other factors associated with reading proficiency in the deaf population, and how the present results for the deaf population compare with developmental and theoretical research in the hearing population.

Overall Effect Size

PCA skills have been extensively investigated in the deaf population. Over 2,000 individuals, born severely to profoundly deaf, have participated in studies investigating PCA skills. Of studies that experimentally tested PCA skills, half reported a statistically significant effect and half did not. The result indicates that some individuals who are deaf exhibit PCA skills. This particular finding has been known for some time as attested by individual studies (Conrad, 1979). However, this result further indicates that many deaf individuals do not show evidence of using PCA skills. The nearly equal distribution of significant effects across studies and participants suggests that the effect size for PCA skills in the deaf population is not large.

The crucial question is the extent to which PCA skills account for reading achievement in the deaf population. Across the 25 studies that measured both PCA and reading skills, the mean effect size (z) was 0.35. Using a range of approaches to average across studies (i.e., using more or less conservative measures to account for missing data and weighting individual study effect sizes based on the number of subjects), the mean effect size increased slightly to 0.40 but remained within the confidence interval. An effect size of 0.35 is classified as a "low to medium" effect (Rosenthal, 2000). A more useful way of conceptualizing effect size is how it translates to variance.

The meta-analysis results indicate that 11% of the variance in reading ability among deaf individuals is explained by PCA skills. The variance explained does not necessarily indicate a causal relationship between PCA skills and reading; such a relationship could only be identified using longitudinal paradigms and then it would be necessary to rule out mediating and confounding factors, as we elaborate below. Rather, the variance explained reveals an associative relationship between the two abilities, PCA and reading. This shared variance does not indicate the direction of the relation. Some researchers argue that PCA skills arise from learning to read (Castles & Coltheart, 2004; Castles et al., 2003). Also, the range of effect sizes across the studies was large. In order to identify the potential factors modulating to this range, we examined individual study characteristics that might explain the range and other factors in the studies that correlated with reading achievement.

Experimental Paradigms: Effect Size and Study Design

Careful scrutiny of the experimental paradigms used across the studies yielded informative results. First, the most common paradigms employed rhyme judgments, and these studies showed PCA effect sizes close to the overall average. Although rhyme judgments were commonly employed, some studies reported that some deaf participants were unfamiliar with the concept. Several authors pointed out that, before administering the test phase of the experiment, the participants had to be familiarized with the concept of rhyme. This poses a problem in interpreting task performance as either true reflection of PCA ability or a more general assessment of familiarity with a concept that is considered common among hearing children but may be foreign to deaf children. Some researchers attempted to address this concern by administering a pretest to the participants to assess their familiarity with the concept of rhyme. This often led to the elimination of a significant proportion of participants from the remainder of the experiment (e.g., Campbell & Wright, 1988).

Research paradigms that employed pseudowords as stimuli, which prevented the deaf participants from using an orthographic strategy to perform the task, showed the smallest effect sizes. This suggests that many deaf readers may use alternative strategies to recognize written words. Indeed, what is interpreted as sensitivity to phonological features of the stimuli in some studies could, in fact, reflect a strategy where orthographic overlap is being used to accurately perform the task. For example, the rhyming set "cat, bat, and hat" all share two out of three letters and thus

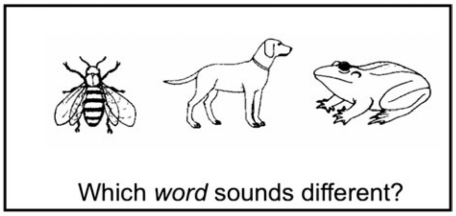

Figure 4 Example of a possible stimuli for a rhyme judgment task (pictures taken from the International Picture Naming Project, retrieved from the UCSD Center For Research on Language IPNP, http://crl.ucsd.edu/~aszekely/ipnp/index.html).

are visually much more similar to one another than three words which share no common letters. In tasks where participants are asked to look at written words of this nature and judge whether or not they rhyme, it is impossible to know whether they are basing their decisions on phonological or orthographic knowledge. This becomes increasingly likely with older participants who have had more exposure to orthographic patterns through reading.

One approach that avoids the orthographic confound is to use pictures instead of written words. In such tasks, children are shown pictures of objects and asked to name or identify the objects that rhyme, as shown in Figure 4. Several versions of this picture-matching task have been used, beginning with Harris and Beech (1998), who adapted the task from Bradley and Bryant (1983) for prereading children. However, even in this case, if children are familiar with the spelling of the objects being pictured, they could still rely on an orthographic strategy. Harris and Beech say of their stimuli that, "there was a close correspondence between the spelling of words and their sounds. Thus, in principle, a child who knew how to spell the words in question could have used spelling (either orthography or fingerspelling) to identify the odd word out" (p. 210).

One way to control the influence of orthography in rhyme tasks is to use rhyming words that differ in their orthography, also known as "orthographically incongruent." For example, Weaver-Trumble (1996) used a word recall task in which participants were presented with lists of words that were phonetically similar but orthographically distinct (e.g., "two, blue, who, chew, shoe, through"). As an additional control, they included lists that were orthographically similar, yet phonetically distinct (e.g., "bear, meat, head, year, learn, peace"). LaSasso and colleagues (2003) used a rhyme-generation task in which participants were required to write as many rhymes as possible for a target word. In this case, the experimenters scored all rhymes as correct or incorrect but calculated separately the words that were orthographically similar and dissimilar to the target. In this way, it was possible to remove words that may have been generated by using a strategy of varying only the initial letter.

In the present meta-analysis, orthographic effects could only be analyzed to the extent that they were controlled in each study. In some cases (Hanson & McGarr, 1989), the experimenters calculated a correlation between phonological coding and reading separately for total rhymes and for those that were orthographically dissimilar to the target in a rhyme-generation task. In other cases (Weaver-Trumble, 1996), orthographic congruence was an experimental control, yet responses to orthographically similar and dissimilar rhymes were considered together when correlated with reading ability. Thus, it was impossible to eliminate the orthographic confound entirely when calculating the overall relationship between phonological coding and reading in the present results.

The results also revealed that studies employing tasks developed for hearing children without adaptation to deaf children yielded effect sizes so large that they fell outside the 95% confidence interval of the analyzed studies. Two studies (Luetke-Stahlman & Nielsen, 2003; Spencer, 2006) used tasks that relied exclusively on auditory presentation and vocal responses from the participants[4]. These tasks required the participants to produce a spoken response at either the syllable or phoneme level. A third study (Colin et al., 2007) included a subtask that required a vocal response. Colin and colleagues did not use a standardized phonological awareness task; however, they did require participants to vocally produce words that rhymed with a target picture. Across the four tasks that required participants to produce a vocal response, the mean effect size was 0.71. Compared to the overall mean of 0.35, this effect size is more than 1 *SD* higher and includes two of the three highest task-specific effect sizes. Because the deaf participants were presented with the PCA task orally and required to produce a vocal response, it is possible that hearing loss and speech ability were being assessed rather than the phenomenon of PCA itself.

Absent from the studies analyzed here was the factor of reading frequency or reading habits. Reading frequency has been shown to have large effects on the reading proficiency of hearing individuals, including those with learning disabilities (Gottardo, Siegel, & Stanovich, 1997; Stanovich, 1986; Stanovich & Cunningham, 1993; Stanovich & West, 1989). Avid reading is a characteristic of skilled as compared to less skilled readers among deaf adults who sign (Chamberlain & Mayberry, 2008). The most accurate research portrayal of reading development in the deaf population thus requires that reading frequency in addition to reading and language levels be measured.

Beyond PCA: Additional Factors Predicting Reading in Deaf and Hearing Populations

Among the other factors measured in the studies, overall language ability, measured in either signed or spoken languages, was found to predict a greater amount of variance (35%) in reading ability than PCA skills (11%). Although this result comes from a limited set of studies, it suggests that language ability may have an even greater influence than PCA on reading development. This result parallels findings from hearing children (Catts, Hogan, & Adolf, 2005; Scarborough, 2005) and suggests that the importance of PCA for reading may be overstated in the literature, especially in work where PCA skills are used as a proxy for hearing and speech skills. Deaf readers, like hearing readers, are more likely to become successful readers when they bring a strong language foundation to the reading process.

Research with the hearing population has found that language ability plays a key role in reading achievement. Large-scale studies of hearing readers that have measured PCA in addition to language skills have found that language plays an enduring role in reading development, one that overshadows the contribution of PCA skills (Catts et al., 1999; Dickenson et al., 2003; Roth, Speece, & Cooper, 2002). Middle school students identified as having reading difficulties have also been found to have language problems (Leach, Scarborough, & Rescorla, 2003; Scarborough, 1990). For students reading at the third grade level and beyond, vocabulary, grammatical, and listening comprehension skills account for more of the variance in reading ability than do PCA skills (Catts et al., 2005; Nation & Snowling, 2004; Scarborough, 2005; Torgensen, Wagner, & Rashotte, 1997). PCA skills are of little help to readers when many words are unknown to them. Many deaf children have significantly underdeveloped language skills in either spoken or signed language.

Across the studies analyzed here, the PCA effect size did not show systematic variation in relation to the reading grade level of the deaf participants, that is, effect sizes were not greater for beginning as compared to advanced readers (or vice versa), but instead showed a wide range across grade levels. This result is consistent with the interpretation that some successful deaf readers employ PCA skills, whereas other successful deaf readers implement alternative strategies and that neither approach is more closely related to reading proficiency in the deaf population than the other.

Finally, it is important to note that the use of alternative strategies to recognize written words is consistent with theoretical models of reading. For example, *dual route* models postulate that one path to word meaning, called the *indirect* route, uses sublexical structure to translate letters into phonemes in order to access word meaning (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). When spelling–sound relationships are regular, as in the words *bat, cat*, and *pat*, the indirect route can be used which uses PCA skills. However, words with a regular spelling–sound correspondence display consistent orthographic patterns that can be learned through their statistical regularities without reference to phonology (Massaro, 1980). The model also postulates a second path, the *direct* route, where word meaning is accessed without the mediating step of phonological coding. The direct route is used for words that have irregular spelling–sound rules (such as the words *have* or *laugh*) and, importantly, for frequent or highly familiar words (Coltheart et al., 2001). The direct route does not recruit PCA skills.

Reading models based on computer simulations, such as parallel distributed processing, also incorporate the notion of alternative paths to phonological coding. These models postulate the existence of multiple and interdependent pathways from print to meaning. Phonological coding is not prioritized in such models. Instead, the pathways work simultaneously using all available information, orthographic, phonological, and semantic, in a race toward word meaning. As the learner becomes familiar with the statistical properties of written words through reading experience, the relative weight allocated to each information source changes (Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). In other words, the sources of information the reader uses for comprehension change over time as reading develops. Thus, the present findings are compatible with theoretical models of reading.

Summary and Conclusions

The goal of this article was to obtain a clear and detailed picture of the relation of PCA skills to reading proficiency in the deaf population by analyzing the experimental designs and statistical outcomes of all the available research with a meta-analysis. The results showed that a wide array of paradigms have been used to investigate this theoretical construct in an already widely varied population. Because the methodologies employed have been so diverse, our approach was to carefully scrutinize them to identify the factors that can influence the results. The present meta-analysis demonstrates just how complex the question is. The results show that the relation of PCA skills to reading proficiency in the deaf population is both moderate in size and highly variable depending upon the nature of the task. The results do not address the direction of the relationship. Some tasks used to measure PCA skills have inherent confounds that mask the theoretical construct being tested, such as orthographic, language, hearing, and speech factors. Many studies measure PCA skills but not reading ability. Many other studies measure PCA and reading skills but not language ability.

The present results are fully consistent with the educational approach of teaching deaf students overt strategies to learn to recognize words. Automatic word recognition is essential to the development of proficient reading, which is why the question of how individuals who are deaf achieve this feat is of enormous educational and theoretical importance. The present results indicate that recognizing written words solely via spoken phonology is moderately associated with reading achievement in the deaf population, as is the case for the hearing population. This means that reading instruction of deaf children requires an educational focus on linguistic as well as word recognition skills. The findings supporting this conclusion are that much variance in reading achievement is unexplained by PCA skills and that other factors, most notably language skill, are highly associated with reading achievement in this population. In parallel with findings from hearing readers, we suggest that further research be undertaken to identify the specific influence of language ability on reading and discover which strategies for teaching word recognition skills produce the best success for deaf readers. We further suggest that intervention efforts focus on building a strong linguistic foundation in deaf students.

Notes

1. These 10 studies were not included in the effect size analysis because effects must be by participants not tasks.
2. Postimplant hearing levels were not reported in the Geers (2003) study.
3. Although we were able to obtain a mean reading grade level for the majority of studies, it is important to note that this mean often represented a wide range within the participants of a given study. In addition, in some cases, only scant information was provided from which to make an estimation, such as “reading approximately 3 years below grade level” or “college level readers.” Thus, reading age information should be interpreted with caution.
4. Spencer (2006) also used several other tests of phonological processing, some of which did not require the use of hearing and speech; however, only performance on the Elision task was used to measure the relationship between phonological processing and reading comprehension.

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Conflict of Interest

No conflicts of interest were reported.

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Appendix A

Studies that met initial criteria for coding but were excluded from final analysis (see text for details, $n = 22$).

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Appendix B

Studies included in the vote count analysis (see text for details, $n = 57$).

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