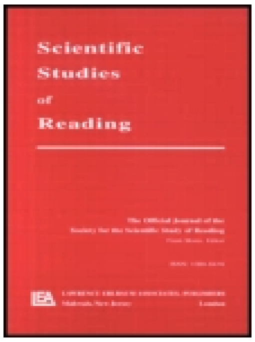

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Reading Difficulties in Adult Deaf Readers of French: Phonological Codes, Not Guilty!

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Deaf people often achieve low levels of reading skills. The hypothesis that the use of phonological codes is associated with good reading skills in deaf readers is not yet fully supported in the literature. We investigated skilled and less skilled adult deaf readers' use of orthographic and phonological codes in reading. Experiment 1 used a masked priming paradigm to investigate automatic use of these codes during visual word processing. Experiment 2 used a serial recall task to determine whether orthographic and phonological codes are used to maintain words in memory. Skilled hearing, skilled deaf, and less skilled deaf readers used orthographic codes during word recognition and recall, but only skilled hearing readers relied on phonological codes during these tasks. It is important to note that skilled and less skilled deaf readers performed similarly in both tasks, indicating that reading difficulties in deaf adults may not be linked to the activation of phonological codes during reading.

Deaf readers' literacy levels are often well below those of their hearing peers (Allen, 1986; DiFrancesca, 1972; Gallaudet Research Institute, 2004; Reinwein, Dubuisson, & Bastien, 2001). Some deaf individuals, however, do reach expert

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reading levels for reasons that are still unclear but that are likely influenced by degree of hearing loss (Conrad, 1979), knowledge of the language that is read (Goldin-Meadow & Mayberry, 2001), age of exposure to a first language (Mayberry, 2007; Padden & Ramsey, 2000), and knowledge of sign language (Chamberlain & Mayberry, 2008; Strong & Prinz, 2000), among other factors.

One hypothesis for poor reading skills in deaf individuals is the (complete or partial) lack of the auditory input necessary for developing fully specified phonological representations. Deaf readers mainly (or uniquely) develop phonological representations through nonauditory channels (i.e., visual lip reading and articulatory speech production). This input may be insufficient for developing fully specified phonological representations (Kelly & Barac-Cikoja, 2007). If the lack of fully specified phonological representations was indeed the main source of reading difficulties, no severely or profoundly deaf reader would become a skilled reader. Several researchers have suggested that only older and better deaf readers use phonological information in reading (e.g., Hanson & Fowler, 1987; Luckner & Handley, 2008; Perfetti & Sandak, 2000). However, some lexical decision studies manipulating word regularity have found no evidence for the use of phonological codes in either skilled or less skilled deaf readers (Chamberlain, 2002; Mayberry, Chamberlain, Waters, & Hwang, 2005; Waters & Doehring, 1990). In a masked priming lexical decision task with pseudohomophone primes (*bloo*), shared phonological codes facilitated responses to target words (*blue*) for hearing adults, but responses were inhibited for deaf adults, suggesting that they processed only the (conflicting) orthographic code (Cripps, McBride, & Forster, 2005). Research on the recall of written words among the deaf population is also unclear as to whether deaf readers use phonological codes (e.g., Waters & Doehring, 1990) or not (e.g., Hanson, 1982, 1990). Only few studies (Hanson, Goodell, & Perfetti, 1991; Hanson, Liberman, & Shankweiler, 1984; Waters & Doehring, 1990) took reading level into account in their analysis. Finally, speech skills (i.e., speech comprehension/production ability but not language skills per se) may also be an important determinant of the use of phonological codes during reading (Hanson, 1986; Perfetti & Sandak, 2000). However, evidence for this relationship is also inconsistent, with some studies supporting the relationship (Hanson, 1986; Leybaert & Alegria, 1993; Transler, Leybaert, & Gombert, 1999) but other studies finding no such relationship (Chamberlain, 2002; Hanson & Fowler, 1987; Hanson et al., 1991).

In sum, deaf people's use of phonological codes during visual word recognition or recall is influenced by many variables, but it is not necessarily a determinant of reading skill in this population. One potential major confound that needs to be addressed is that, due to the tight spelling-sound mappings in alphabetical writing systems, results attributed to the unique effect of phonology could be due to effects of orthography. Because of the important role attributed to phonological codes in reading, particularly in explaining reading difficulties in deaf readers, it is crucial to disentangle the effects of orthographic and phonological codes during word processing to assess the contribution of each code in reading for deaf individuals.

The present experiments investigate the independent contribution of orthographic and phonological information to visual word recognition and memory storage in severely to profoundly deaf adult readers who primarily communicate through sign language. We compared skilled and less skilled deaf readers to determine whether skilled reading requires the use of phonological codes. Waters and Doehring (1990) found that orally educated deaf readers did not use phonological codes during word recognition but did in a recall task. They suggested that there are two different types of phonological codes used during reading (see also Wagner & Torgesen, 1987): one for holding information in memory and one for more automatic processes such as word recognition. We attempted to replicate Waters and Doehring's dissociated use of phonological information with a masked priming experiment task (Experiment 1) and a written word recall task (Experiment 2), which tap different aspects of phonological processing during reading. We included a group of skilled hearing readers in both experiments to ensure replication of orthographic and phonological effects found in the literature and to determine whether word recognition and recall in deaf readers is qualitatively different from that of expert hearing readers.

EXPERIMENT 1

This experiment was based on previous studies (Ferrand & Grainger, 1993, 1994; Grainger & Ferrand, 1996) investigating the time-course of phonological and orthographic information during word processing with French expert hearing readers. We combined the masked priming paradigm using short stimulus onset asynchronies (SOAs) with a lexical decision task to assess early, automatic involvement of orthographic and phonological codes during word processing (Forster, Mohan, & Hector, 2003). Masked priming is more sensitive to phonological effects than regularity effects in lexical decision tasks for hearing readers (Berent, 1997) and therefore provides a stronger test for the use of early phonological codes in deaf readers. We used pseudoword primes to investigate the very early stages of word processing at the sublexical level as proposed by the Bimodal Interactive Activation Model (Diependaele, Ziegler, & Grainger, 2010). The model also proposes that orthographic codes are activated 20 to 30 ms before phonological codes (see Grainger & Holcomb, 2009, for a review). We chose two prime durations, 40 and 60 ms, to tap both orthographic and phonological effects at their most effective priming capacity (Ferrand, 2001). There were four

TABLE 1
Percentage of Orthographic and Phonological Overlap Between Primes and Targets in Each Experimental Condition

	Shared Letters (%)	*Shared Phonemes (%)*
O+P+	76	100
O–P+	48	100
O–P–	45	21
Unrelated	0	0

conditions differing in phonological and orthographic overlap[1] between primes and targets. Word targets were preceded by four types of pseudoword primes[2]: (a) O+P+, the orthographically similar pseudohomophone condition (e.g., bore – BORD); (b) O–P+, the orthographically dissimilar pseudohomophone condition (e.g., baur – BORD); (c) O–P–, the orthographically dissimilar nonhomophonic condition (e.g., boin – BORD); and (d) a phonologically and orthographically unrelated condition (e.g., clat – BORD; see Appendix A). Orthographic processing is measured by comparing the O+P+ condition with the O–P+ condition, as phonological overlap is constant and orthographic overlap is modulated between these conditions (Table 1). Phonological processing is measured by comparing the O–P+ condition with the O–P– condition, as orthographic overlap is constant and phonological overlap is modulated between these conditions (Table 1).

We hypothesized that skilled hearing readers (SKH) will show orthographic priming effects with a 40 ms and a 60 ms prime duration (i.e., slower responses in the O-P+ condition relative to the O+P+ condition) but phonological priming effects only with a 60 ms prime duration (i.e., slower responses in the O–P– condition than in the O–P+ condition; but see Lee, Rayner, & Pollatsek, 1999, for earlier phonological priming effects). For the deaf readers, if good reading skills require the use of phonological codes during visual word recognition (Hanson & Fowler, 1987; Luckner & Handley, 2008; Perfetti & Sandak, 2000), then only the group of skilled deaf readers (SKD) will show phonological effects. In contrast, if phonological processing is not essential for good reading skills, then there will be no difference between both groups of deaf readers in their use (or not) of phonological codes (Chamberlain, 2002; Mayberry et al., 2005; Waters & Doehring, 1990). Skilled deaf and less skilled deaf readers (LSKD) are both expected to use orthographic codes during word recognition.

[1]Phonological overlap was calculated as the number of phonemes shared between a prime and a target. Orthographic overlap was calculated as the number of letters shared between a prime and a target. The letters did not have to be in the exact same position within the prime as they were within the target, but they had to respect the relative position of letters within the target.

[2]O stands for orthographic and P stands for phonological. The + sign indicates that the prime/target pairs share a high percentage of orthographic or phonological information, and the – sign indicates that the prime/target pairs share a lower percentage of either type of information.

Methods

Participants

Twenty-nine adults[3] from Montreal's Deaf community were recruited. All participants (a) were prelingually and severely to profoundly deaf, (b) had learned Quebec Sign Language (LSQ) before the age of 13 and used it as their main communication mode for more than 10 years, and (c) had been educated in French schools. Their ages ranged from 20 to 55 years ($M = 36$, $SD = 10.3$), and they had a mean education level of 15.3 years ($SD = 3.3$ years). All participants reported exposure to at least one other language besides LSQ and French (e.g., English, American Sign Language). Fifteen participants reported having profound hearing loss, 1 reported having severe hearing loss, and 7 reported severe to profound hearing loss. Six participants did not specify their degree of hearing loss but confirmed that they fit the inclusion criteria (severely to profoundly deaf). They were distributed equally between the skilled and less skilled reader groups. No participant had a cochlear implant.

Sixteen hearing adults served as a control group. They all had French as their first language, had medium to high levels of self-reported English skills, and had not been exposed to a third language. Their ages ranged from 20 to 49 years ($M = 31$, $SD = 9.6$), and they had a mean education level of 17 years ($SD = 2.3$).

All participants had normal or corrected-to-normal vision and received financial compensation for their participation.

Background Measures

Reading-level measure. Prior to the experimental task, all participants completed a standardized reading test (*Test de rendement pour francophones*; Sarrazin, 1996). The timed test consisted of short paragraphs followed by multiple-choice questions. The number of correct answers was converted to grade equivalents.

Speech use and comprehension. The deaf participants answered on a scale of 0 to 7 how well they currently understood speech (lip reading) (a) at school/work, (b) with family, (c) with friends, (d) in shops/restaurants, and (e) with strangers.

Stimuli

We adapted the stimuli from Grainger and Ferrand (1996), which originally contained 30 four-letter target words. French target words that were homographs or

[3]Thirty-one participants were tested, but 2 participants were removed from the analyses in Experiment 1, and 1 participant was removed from the analyses in Experiment 2 because these participants did not understand the tasks.

cognates of English words (e.g., *main*, *vent*, *zinc*, *vain*) were replaced to avoid cross-lingual phonological priming effects (Van Wijnendaele & Brysbaert, 2002) as most French Canadians would have been exposed to some English. We added five-letter words to generate enough French items. The final stimuli set had 40 four- to five-letter target words with a mean frequency of 113 occurrences per million (range = 2–1,289/million), and an average of 7 orthographic and 41 phonological neighbors. We also added four- to five-letter nonword targets to complete the lexical decision task. Several types of prime/target pairs were included as fillers to reduce predictability. Thirty-seven nonword prime/nonword target pairs were included. The target nonwords were four to five letters long and, as in the original study (Grainger & Ferrand, 1996), nonword prime conditions matching the four experimental conditions were also used: (a) O+P+ (keit – KAÎT), (b) O–P+ (kets – KAÎT), (c) O–P– (kaum – KAÎT), and (d) an unrelated prime (jode – KAÎT). Finally, 148 unrelated nonword/word pairs and 160 unrelated nonword/nonword pairs were also included. The filler target words were matched in number of letters and frequency with the experimental target words. The fillers were not analyzed.

Design

To reduce subject and item variability, each participant saw each target at each of the eight Prime Type (n = 4) × Prime Duration (n = 2) combinations (see Frost, Ahissar, Gotesman, & Tayeb, 2003, for a similar design). Participants first performed a lexical decision task in which the experimental items were presented twice to reduce the repetition effect in the experimental task (see Frost et al., 2003, for more details). This design is particularly attractive when testing special populations as it may be difficult to attain large enough samples to counterbalance target presentation across participants.

We created four lists, each with 10 experimental prime/target pairs from each prime type, and 114 fillers. Each participant received the eight presentations (Prime Type × Prime Duration) of a target in a different order to avoid order effects. Each list of 154 prime/target pairs was presented as a block, for a total of four blocks per testing session. Each block was separated by a brief pause.

Apparatus and Procedure

We presented the task using DMDX software (Forster & Forster, 2003) on a Pentium 4 PC with a 22-in. iiyama CRT monitor at a refresh rate of 150 Hz. The items were presented centrally in light blue, 14-point Courier New font on a black background.

Participants were seated in front of a computer screen. They performed a forward-masked primed lexical decision task with the following sequence of events: (a) a pattern mask for 500 ms (e.g., #######), (b) a pseudoword prime in lowercase for 40 or 60 ms (e.g., *mert*), and (c) a word or pseudoword target in uppercase for 500 ms (e.g., MÈRE or KAÎT). Participants were instructed to press the Yes or No button on a gamepad to indicate whether or not the uppercase target was a true French word. They were encouraged to respond as rapidly and as accurately as possible. Eighteen practice items were presented at the beginning of the task. The deaf participants received instructions in LSQ from a deaf research assistant. Participants were tested once with each prime duration (40 or 60 ms), with a 10- to 15-day interval between sessions and the order of sessions counterbalanced across participants. Each session lasted about 40 min.

Results

Background Measures

The deaf participants' reading levels ranged from Grade 1 to postsecondary (12+). We used the median (Grade 7.5) as the cutoff for forming the less skilled ($n = 14$; Grade 1–6 reading levels with $M = 4.6$, $SD = 1.6$) and skilled ($n = 15$; Grade 7.5 to above Grade 12 reading levels with $M = 9.5$, $SD = 1.6$) reader groups. All hearing participants scored at the highest level of the reading test (Grade 12+).

A one-way analysis of variance (ANOVA) comparing the reading levels of the SKH, SKD, and LSKD readers resulted in a significant main effect, $F(2, 42) = 125.3$, $p < .0001$, $\eta_p{}^2 = .86$. An *Unequal N HSD* post hoc test showed that the three groups all differed from one another (all ps $< .0001$). We also used a one-way ANOVA to compare the mean number of years of education of the three groups and found a main effect, $F(2, 42) = 4.6$, $p = .02$, $\eta_p{}^2 = .18$. An *Unequal N HSD* post hoc test revealed that only the LSKD ($M = 14$, $SD = 3.5$) and the SKH ($M = 16.9$, $SD = 2.3$) groups significantly differed on educational level ($p = .02$). However, all three groups had means equivalent to postsecondary education levels.

Speech use and comprehension. A mean was calculated from each participant's rating (0–7) across each of the five daily situation. A one-way ANOVA revealed that the SKD ($M = 3.7$, $SD = 1.3$) and LSKD ($M = 3.4$, $SD = 1.1$) reader groups did not differ on this measure ($p = .41$).

Experimental Task Results

As the data for the hearing participants was gathered to replicate the time-course effect of phonological and orthographic priming, hearing and deaf participants' data were analyzed separately. Reaction times (RTs) beyond 2 *SD* from the mean for each participant were removed, resulting in 1.6% and 1.9% of the data being rejected for the hearing and deaf participants, respectively. Only RTs for correct

TABLE 2
Mean Correct Reaction Times (RTs) and Percentage Error (Within Parentheses) for the Four Prime Type Conditions at Each Prime Duration and for Each Group for the Word Targets

Prime Duration and Type	*O+P+* *RT[a] (SD)*	*O−P+* *RT (SD)*	*O−P−* *RT (SD)*	*Unrelated* *RT (SD)*
40 ms				
SKH	540(4.6)	548(5.7)	546(4.8)	556(5.4)
SKD	562(6.6)	568(7.4)	567(5.5)	581(7.1)
LSKD	604(9.2)	615(10.2)	611(7.7)	626(9.8)
60 ms				
SKH	541(4.4)	553(5.5)	563(6.8)	560(6.2)
SKD	575(7.5)	592(7.8)	599(6.5)	603(5.5)
LSKD	612(9.1)	627(10.3)	636(8.7)	642(11.4)

Note. SKH = skilled hearing readers; SKD = skilled deaf readers; LSKD = less skilled deaf readers.

[a]RTs are in milliseconds.

responses to the experimental stimuli and error data were analyzed. Data were analyzed using a linear-mixed effect (lme) model with subjects and items specified as crossed random effects (Baayen, 2008; Baayen, Davidson, & Bates, 2008) using the lme4 package (Bates, Maechler, & Dai, 2009) available in the R environment (R Development Core Team, 2008). The *p* values were computed with Markov-Chain Monte Carlo sampling (with the pvals.fcn function from the languageR package; Baayen, 2008). To obtain a measure of overall priming (O+P+ vs. Unrelated), orthographic priming (O–P+ vs. O+P+), and phonological priming (O–P– vs. O−P+), contrasts were set up within the specified model using successive difference contrasts[4] (Venables & Ripley, 2002). Prime duration (40 ms and 60 ms) and group (SKD and LSKD for deaf participants' analysis) were included in the model as categorical factors. Target order was included as a continuous variable to examine repetition effects on the different priming levels. The mean RT and accuracy data are presented in Table 2.

[4]To perform the successive difference contrasts, conditions were analyzed in the following order: 1 = Unrelated, 2 = O+P+, 3 = O–P+, and 4 = O–P–. The first contrast compared Condition 2 versus Condition 1 to get a measure of overall priming. Because of the way the analyses were set up, for the overall priming contrast (O+P+ minus Unrelated) the regression coefficient estimates should be negative (but would indicate facilitation because it is expected that the O+P+ condition should be responded to faster than Unrelated condition). The second contrast compared Condition 3 versus Condition 2 to get a measure of orthographic priming. Finally, the third contrast compared Condition 4 versus Condition 3 to get a measure of phonological priming. These two contrasts should yield positive regression coefficient estimates, which would be indicative of orthographic and phonological facilitation effects.

Hearing participants. Results revealed a significant three-way interaction between target order, orthographic contrast, and prime duration ($b = 19.54$, $SE = 5.55$, $p = .0001$) and a nearly significant three-way interaction between target order, phonological contrast, and prime duration ($b = -10.60$, $SE = 5.60$, $p = .06$). Therefore we analyzed each prime duration condition separately. As expected, at 40 ms, orthographic priming (O–P+ vs. O+P+; $b = 8.74$, $SE = 4.29$, $p = .0015$) and overall priming effects (Unrelated vs O+P+; $b = -15.40$, $SE = 4.31$, $p < .0001$) were significant. Phonological priming (O–P– vs. O−P+ ; $b = -3.79$, $SE = 4.31$, $p = .25$), target order, and interaction effects were not (all ps > .08). At 60 ms, the orthographic ($b = -20.81$, $SE = 10.68$, $p = .05$), phonological ($b = 25.23$, $SE = 10.67$, $p = .02$) and overall ($b = -26.78$, $SE = 10.73$, $p = .01$) priming effects were all significant. The Orthographic Priming × Target Order interaction was significant ($b = 12.76$, $SE = 3.89$, $p = .001$), indicating that orthographic priming was modulated by target order.

Deaf participants. Two separate analyses were run for the 40 ms and 60 ms prime durations. At 40 ms, orthographic priming was significant ($b = 27.76$, $SE = 8.99$, $p = .002$), overall priming approached significance ($b = -16.64$, $SE = 8.99$, $p = .06$), and phonological priming was not significant ($b = -1.33$, $SE = -1.47$, $p = .88$). The LSKD readers also had significantly longer RTs than SKD readers ($b = 61.39$, $SE = 30.33$, $p = .04$). Crucially, there were no interactions between priming contrasts and group (all ps > .16), indicating that LSKD and SKD readers were not differentially affected by different prime types when processing targets. Orthographic priming was again modulated by target order ($b = -6.89$, $SE = 3.30$, $p = .04$).

Similar effects emerged at 60 ms. Both the orthographic and overall priming effects were significant ($b = 15.45$, $SE = 5.06$, $p = .002$ and $b = -26.64$, $SE = 5.07$, $p < .0001$, respectively), whereas the phonological priming was not ($b = 7.83$, $SE = 5.07$, $p = .12$). The effect of group was not significant ($b = 41.37$, $SE = 28.29$, $p = .14$). Again, none of the interactions between priming contrasts and group were significant (all ps > .76). Overall priming was modulated by target order ($b = 10.56$, $SE = 3.29$, $p = .001$), but orthographic priming was not ($b = -4.21$, $SE = 3.28$, $p = .20$).

An analysis of the error data at 40 ms revealed significant interactions between target order and orthographic priming ($b = 0.33$, $SE = 0.16$, $p = .04$), and between target order and phonological priming ($b = -0.47$, $SE = 0.16$, $p = .003$). The main (group and priming) and interaction (Priming Contrasts × Group) effects were not significant (ps > .07). The 60-ms analyses revealed no significant main or Phonological × Group interaction effects (all ps > .23), but significant interactions between overall priming and group ($b = -2.21$, $SE = 0.98$, $p = .02$) and between orthographic priming and group ($b = 1.83$, $SE = 0.88$, $p = .04$). LSKD readers made more errors than SKD readers when there was less orthographic overlap between primes and targets, but, similar to the RT analyses, both groups responded similarly when there was phonological overlap between primes and targets.

Finally, we conducted a linear regression analysis with net phonological priming[5] predicting reading level. The result was not significant ($R^2 = .001$, $p = .86$), supporting the lme results. Speech comprehension predicted neither net phonological priming ($R^2 = .04$, $p = .31$) nor reading level ($R^2 = .024$, $p = .42$).

Discussion

The results for the hearing participants replicated the results found in the literature. This supports a time-course hypothesis of information processing in visual word recognition in which orthographic information is activated slightly earlier than phonological information (Grainger & Holcomb, 2008) and provide more evidence for the early computation of phonological codes as predicted by the Bimodal Interactive Activation Model (Diependaele et al., 2010).

Our results, consistent with previous research, also show that both deaf reader groups use orthographic information during word processing at both prime durations (Burden & Campbell, 1994; Chamberlain, 2002; Daigle, Armand, Demont, & Gombert, 2009; Harris & Moreno, 2004; Miller, 2006, 2007).

Crucially, however, our results show that phonological information did not affect target processing for severely to profoundly deaf skilled *and* less skilled readers of French who communicate through sign language. This is consistent with prior research suggesting that adult deaf readers do not activate phonological codes during English written word recognition (Chamberlain, 2002; Cripps et al., 2005; Waters & Doehring, 1990). This finding is important as it is one of few studies showing that skilled and less skilled deaf readers do not differ in the way they process written words, at least when it comes to the use of orthographic and phonological codes. The regression result showing that deaf participants' use of phonological codes did not predict their reading level further reinforces this finding. In addition, speech comprehension skills in deaf readers were not predictive of net phonological priming effects and reading level (Chamberlain, 2002; Hanson & Fowler, 1987; Hanson et al., 1991), suggesting that better lipreading skills do not translate into better reading. The error analyses revealed no main or interaction effects of group and phonological contrast at both prime durations, indicating that phonological information did not affect skilled or less skilled readers' word recognition accuracy.

[5]Net phonological priming effects were calculated as the difference in reaction times between the O–P+ and the O–P– conditions for the 60 ms prime duration data, where phonological priming is most likely to occur.

Our results present a more fine-grained portrait than previous research in suggesting that, for deaf readers, prelexical phonological information was not computed early with briefly presented pseudoword primes. It is possible, however, that deaf readers compute phonological codes more slowly (and were not detected with such short SOAs) or later in word processing (lexically or postlexically). This possibility would be consistent with previous research finding phonological effects in tasks that are not as sensitive to early phonological effects and allow for postlexical generation of phonological codes (Dyer, MacSweeney, Szczerbinski, Green, & Campbell, 2003; Hanson & Fowler, 1987).

In sum, our findings showed that deaf readers with a wide range of reading skills show orthographic information processing during word recognition (like hearing readers) but do not use sublexical phonological codes in early word processing (unlike hearing readers). Overall, our results support the hypothesis that deaf readers "recognize words in a qualitatively different way from hearing readers" (Chamberlain, 2002, p. 222), at least when using sublexical phonological codes in early word recognition.

EXPERIMENT 2

Experiment 2 investigated the use of orthographic and phonological codes to retain words in memory. Hearing participants are poorer in recalling lists of phonologically similar words than lists of phonologically unrelated words, even when the words are presented visually (see Baddeley & Logie, 1999, for a review; Conrad & Hull, 1964). Waters and Doehring (1990) suggested that oral deaf readers do not use phonological codes during written word recognition but do retrieve them to maintain visually presented words in memory. However, their findings in their recall task could have been due exclusively to the use of orthographic codes as there was no phonologically similar and orthographically dissimilar condition in their experiment. Therefore we investigated the independent use of orthographic and phonological codes to maintain words in memory.

In a serial recall task manipulating the orthographic and phonological overlap between words, we expected that SKH readers would be disrupted by phonological similarity. We also expected that they would use orthographic codes to maintain words in memory above and beyond the use of phonological codes (i.e., recall more phonologically and orthographically similar words than only phonologically similar words). Also, if deriving phonological codes during visual word recall is essential for good reading skills, we predicted that only the SKD readers would show effects of phonological similarity (Hanson et al., 1984), but that both SKD and LSKD readers would use orthographic codes.

Methods

Participants

Participants were the same as in Experiment 1.

Background Measures

These were the same as in Experiment 1.

Stimuli

We found six words for the orthographically and phonologically similar condition (O+P+: *pierre*, *équerre*, *verre*, *lierre*, *serre*, *erre*) and for the orthographically dissimilar and phonologically similar condition (O–P+: *bière*, *chair*, *clerc*, *enfer*, *serf*, *affaire*). We could not match these lists on the number of letters, number of phonemes, and frequency (although the differences were minimal), so we constructed two control lists of orthographically and phonologically unrelated words to match the respective experimental lists on these variables (see Appendix B). Therefore, our stimuli pool included four conditions, each with six words.

To determine the effect of phonological codes, we compared the number of words recalled in the O–P+ experimental list to that recalled in the O–P+ control list, as the lists differed only in the amount of phonological overlap between items. We compared the O+P+ experimental and the O+P+ control lists to measure the use of both codes. Finally, to determine the use of orthographic codes to maintain words in memory, we compared the O–P+ and the O+P+ experimental conditions.

Design

We constructed 48 lists from the stimuli, with 12 lists in each of the four conditions. Each of the 12 lists in a condition included five different words taken from the corresponding condition stimuli pool, and each word never appeared more than twice in the same position across the 12 lists. Participants saw all 48 lists in one of two counterbalanced orders.

Procedure and Apparatus

We used the same apparatus and software as in Experiment 1. Words were presented in light blue, 12-point Courier New font on a black background. Deaf participants received instructions in LSQ from a deaf research assistant. To ensure familiarity with the words, participants were first given a list of the words with corresponding illustrations and brief written definitions. During the task, the items in a list were individually presented at the rate of one word per second. At the end of each list, participants wrote down as many items as possible, in the same order as presented, in a booklet (one list per page). Participants were given four practice lists of five items each.

Results

We calculated the mean number of words recalled correctly in order for each condition. We analyzed the separate and combined effects of phonological and orthographic codes with separate lme models (Baayen, 2008; Baayen et al., 2008) for the hearing and deaf participants. The *p* values were computed with Markov-Chain Monte Carlo sampling (Baayen, 2008).

To determine the effects of orthographic codes (O–P+ and O+P+ lists), phonological codes (O–P+ and O–P+ control), and orthographic and phonological codes combined (O+P+ and O+P+ control), we set up contrasts between lists within the lme models using successive difference contrasts[6] (Venables & Ripley, 2002). Lists (O+P+, O+P+ control, O–P+, O–P+ control) and group (SKD and LSKD, for deaf participants only) were categorical factors in the models. Each group's net difference between the mean number of items recalled for each contrast (orthographic, phonological, and orthographic and phonological) is presented in Figure 1.

Hearing Participants

There was a highly significant effect of phonological similarity ($b = 0.85$, $SE = 0.13$, $p < .0001$), with hearing participants recalling fewer rhyming (O–P+ experimental) than control (O–P+ control) items (Figure 1, panel A). There was no significant effect of combined orthography and phonology (O+P+ experimental vs. and O+P+ control lists, $b = -0.09$, $SE = 0.19$, $p = .47$). Finally, there was a significant effect of orthographic similarity ($b = -0.43$, $SE = 0.12$, $p = .0005$), indicating that participants recalled more words sharing both phonology and orthography (O+P+ lists) than words sharing only phonology (O–P+ lists). Thus orthographic information helped hearing participants maintain words in memory, but phonological similarity was inhibitory.

[6]To perform the successive difference contrasts, lists were analyzed in the following order: 1 = O+P+ control, 2 = O+P+, 3 = O–P+, and 4 = O–P+ control. The first contrast compared Condition 2 versus Condition 1 to get a measure of combined orthographic and phonological encoding. Better recall of items in the O+P+ list relative to the O+P+ control list will result in a negative regression coefficient estimate; similarly for the measure of orthographic encoding (Condition 3 vs. Condition 2). Because of the way the analyses were set up (Condition 4 vs. Condition 3), if an inhibitory effect of phonologically similar words is found (fewer items would be recalled in the O–P+ list than in the O–P+ control list), the regression coefficient estimate will result in a positive value.

Deaf Participants

There was no significant group effect (SKD vs. LSKD, $b = 0.48$, $SE = 0.31$, $p = .12$) or interaction effect between group and the different contrasts (phonology, orthography, and combined; all ps $>.66$), indicating that both deaf reader groups responded similarly across conditions. There was also no significant effect of phonology (O–P+ experimental vs. O–P+ control; $b = 0.15$, $SE = 0.12$, $p = .21$), suggesting that deaf participants, regardless of reading skill, were not influenced by the phonological relationship between words and were thus not inhibited by phonological similarity (Figure 1, panel B). There was a significant combined effect of orthography and phonology (O+P+ experimental vs. O+P+ control; $b = 0.34$, $SE = 0.12$, $p = .004$). As the previous contrast showed no phonology effect, it is safe to say that the difference between the O+P+ experimental and O+P+ control conditions is purely orthographic. Finally, there was a significant orthography effect, ($b = -0.32$, $SE = 0.12$, $p = .006$), indicating that deaf participants recalled more words sharing both orthography and phonology (O+P+) than words sharing only phonology (O–P+). This result suggests that deaf readers use orthographic information to maintain words in memory (see Figure 1, panel B).

As in Experiment 1, we performed linear regression analyses for the deaf participants to determine whether (a) the use of phonological codes predicted reading level or overall memory span (i.e., mean number of words recalled across all conditions); (b) overall memory span predicted reading level; and (c) speech comprehension predicted overall memory span, reading level, or the use of phonological codes to maintain words in memory. Memory span was a significant predictor of reading level ($R^2 = .49$, $p = .007$), paralleling the trend found for

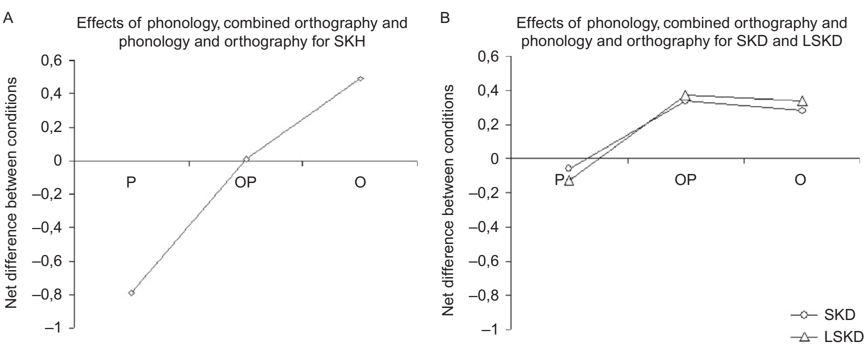

FIGURE 1 Effects of phonology (P), combined orthography and phonology (OP), and orthography (O) during recall for skilled hearing headers (SKH), skilled deaf readers (SKD) and less skilled deaf readers (LSKD).

the group effect in the lme analyses. All other regressions were not significant (R^2s $< .33$, ps $> .09$).

Discussion

Experiment 2 showed that both hearing and deaf readers used orthographic codes to maintain words in memory (Chincotta, Underwood, Ghani, Papadopoulou, & Wresninski, 1999; Logie, Della Sala, Wynn, & Baddeley, 2000). As expected, skilled hearing readers were affected by phonological similarity between visually presented words during recall (see Baddeley & Logie, 1999, for a review). In contrast, deaf readers did not derive phonological codes to maintain written words in memory; this result is different from Waters and Doerhing's (1990) study showing that orally educated deaf readers did use phonological codes to maintain visually presented words in memory. The previous effect could have been due exclusively to the use of orthographic codes, however, as Waters and Doerhing's rhyming stimuli were also orthographically similar. Our striking result is that skilled *and* less skilled deaf readers encoded written words in memory similarly: Both groups used orthographic but not phonological codes. Although the deaf reader groups differed in reading comprehension and memory span (also highly predictive of reading level), their use of phonological codes did not predict their reading level or memory span. Finally, as in Experiment 1, the present results showed that speech skills did not predict the use of phonological codes and did not predict reading level or memory span.

Most important for the hypotheses tested, we cannot conclude that less skilled deaf readers' reading difficulties are caused by the lack of use of phonological codes in memory because skilled deaf readers also did not use such codes to recall written words. Therefore, an additional factor beyond the use of phonological codes in memory might drive reading and memory span differences among deaf readers.

GENERAL DISCUSSION

Our experiments investigated the use of orthographic and phonological codes during visual word recognition and recall and whether the use of phonological codes determined skilled reading in severely to profoundly adult deaf readers. We used two tasks to tap both the prelexical (priming with pseudoword primes) and the postlexical (recall task) use of orthographic and phonological codes in written word processing.

In both experiments, the performance of skilled hearing readers was consistent with previous research. They showed dissociated effects of orthographic and phonological information, with a different time-course for each code in word recognition (Ferrand & Grainger, 1994; Lee et al., 1999; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000), and an inhibitory effect caused by phonological similarity between written words (Baddeley, 1966; Conrad & Hull, 1964). These results support the validity of our tasks. Skilled hearing readers also showed use of orthographic codes to maintain words in memory, which is, again, consistent with previous research (Chincotta et al., 1999; Logie et al., 2000).

It is important to note that the skilled and less skilled deaf readers showed identical patterns of use of orthographic and phonological codes in both tasks. Experiment 1 showed that deaf readers, whether skilled or less skilled, use orthographic but not phonological codes prelexically during word recognition. However, it was unclear whether deaf readers may instead have access to lexical or postlexical phonological codes during reading (Waters & Doehring, 1990). Experiment 2 examined this hypothesis and showed that deaf readers were not affected by phonological similarity during written word recall, which would have allowed for lexical phonological access. It could also be argued that the absence of phonological effects can be due to both experiments using the same participants. However, this is unlikely, as we used two very different tasks tapping different aspects of phonological processing (Wagner & Torgesen, 1987) yet found similar results. Finally, although our participants were deaf readers of French, the effects we replicated for the hearing readers of French are generally robust across languages (Frost et al., 2003; Lee et al., 1999; Weekes, Chen, & Lin, 1998). Thus our results for deaf participants are also likely to transfer to other languages, although further research is needed to investigate this issue.

The results of Experiments 1 and 2 together strongly support the view that, at least for adult severely to profoundly deaf readers who primarily use sign language, the use, or lack of use, of phonological codes is not a determinant of reading level and not a key cause of reading difficulties. Neither skilled nor less skilled deaf readers used phonological codes in either task. In addition, in both experiments, their speech comprehension skills did not predict their use of phonological codes or their reading level, and their use of phonological codes did not predict their reading level (Chamberlain, 2002; Hanson & Fowler, 1987; Hanson et al., 1991).

For hearing readers, phonological codes are developed prior to reading and provide a basis on which orthographic codes can be built during reading development (Frost, 1998). Phonological codes are the most powerful cues hearing readers have to help them decode unfamiliar written words and retrieve words from memory if they know the word orally. For deaf readers, phonological codes may not be as usable during word recognition, and therefore may not be essential for attaining skilled reading. Our results are in line with Goldin-Meadow and Mayberry's (2001) conclusion that "phonological . . . knowledge may not serve the same functions during reading [for deaf readers] that it does for hearing readers" (p. 224). Deaf readers may learn to map orthographic representations directly to meaning and develop stronger orthographic representations as they are increasingly exposed to print (Harris & Moreno, 2004), even if these representations are developed at a slower rate than those of young hearing readers (Daigle et al., 2009).

Finally, although working memory models, such as the multicomponent model (Baddeley, 2003), place great emphasis on speech-based encoding for verbal materials, Hall and Bavelier (2010) have proposed the *Multiple-Coding Hypothesis*. This view of memory encoding posits that as many codes as possible are used to maintain words in memory. Research shows that orthographic (Chincotta et al., 1999; Logie et al., 2000) and semantic codes (Haarmann, Davelaar, & Usher, 2003; Martin, 2005; Shivde & Thompson-Schill, 2004) are also used to maintain written words in memory. Hall and Bavelier further proposed that deaf people viewing sign language and hearing people listening to speech may rely differently and preferentially on one or more of the multiple activated codes (i.e., not necessarily and principally on speech-based codes). We similarly suggest that deaf readers may rely on codes that are more readily available to them, such as orthographic, semantic, tactile, and even sign or fingerspelling encoding (Lichtenstein, 1998; McQuarrie & Parrila, 2009; Treiman & Hirsh-Pasek, 1983) when maintaining written words in memory.

In sum, the present results suggest that phonological codes are not the crux of the reading difficulties experienced by deaf readers, as even skilled deaf readers did not activate phonological codes during word recognition or recall. Although more research is necessary to confirm this hypothesis, the present results are compelling because they were found across two different tasks and participant reading levels. Reading instruction for young deaf readers may be highly focused on teaching spelling-sound correspondences, but this particular aspect of reading may not be the one that carries the most weight over time (Mayberry, Del Giudice, & Lieberman, 2011). Therefore, it may be worthwhile for researchers and practitioners working with deaf children to step back and view reading more globally than uniquely in relation with phonological coding.

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APPENDIX A

Stimuli Used in Experiment 1

Targets	*O+P+*	*O–P+*	*O–P–*	*Unrelated*
AISE	aize	èzze	oube	toul
BAIN	baim	bint	baun	dour
BANC	bant	bemp	bour	moir
BELGE	belje	bailj	banne	daune
BERGE	berje	bairj	blote	clond
BORD	bore	baur	boin	clat
CERF	cers	sair	neul	nise
CHAUD	shaud	sheau	phape	herfe
CHOSE	choze	shauz	vhimp	vram
CRAIE	crais	krèts	grice	geuf
DAIM	dain	dint	dams	lenf
ENCRE	enkre	amkre	chlèr	paxpe
FAIM	fain	fint	foum	neur
FAIT	faie	fets	folt	sule
FAUX	faud	fots	foig	seil
FILS	fiss	phys	caks	ceme
FLOT	flos	flau	fouk	dien
GREC	grek	graik	gleum	doir
HAUT	haux	hôts	heit	reil
MAUX	maut	meau	muxe	sede
MÈRE	mert	mair	mune	siul
NAIN	naim	nint	nine	fule
NEIGE	neije	naije	noine	crops
NERF	nert	nair	nilf	couar
NORD	nore	naur	nade	sate
PAUSE	pauze	pozze	peife	noilk
PIEGE	pieje	piaij	plare	daque
PLAIE	plais	plets	paufe	chage
POCHE	poshe	paush	paune	juine
PORC	pord	paur	pacs	tabe
SAIN	saim	sint	sanf	nour
SINGE	sinje	seinj	saune	duate
SOIE	sois	swas	sruc	vure
TAIE	taix	tèts	taum	goul
TAUX	taud	tots	treg	dile
TEMPS	temts	tands	trige	ruilf
THYM	thyn	tein	trid	peul
TORT	tors	taur	tite	bind
VEAU	vhau	vots	vlon	clon
VERT	verd	vair	vons	doin

APPENDIX B

Characteristics of the Stimuli Used in Experiment 2

	Frequency	*No. Letters*	*No. Phonemes*	*No. Syllables*		*Frequency*	*No. Letters*	*No. Phonemes*	*No. Syllables*
Orthographically similar rhyming (O+P+)					Orthographically Dissimilar Rhyming (O–P+)				
pierre	119.39	6	4	1	bière	35.41	5	4	1
équerre	1.49	7	4	2	chair	90.81	5	3	1
verre	175.2	5	3	1	clerc	5.68	5	4	1
lierre	6.08	6	4	2	enfer	38.78	5	4	2
serre	4.53	5	3	1	serf	0.27	4	3	1
erre	0.74	4	2	1	affaire	150.54	7	4	2
M	51.24	5.50	3.33	1.33	*M*	53.58	5.17	3.67	1.33
Controls for O+P+					Controls for O–P+				
ventre	136.69	6	4	1	plume	33.38	5	4	1
manchot	1.49	7	4	2	tante	110.95	5	3	1
cause	188.04	5	3	1	fable	5.81	5	4	1
guidon	6.22	6	4	2	avion	46.82	5	4	2
miche	4.59	5	3	1	fève	0.61	4	3	1
faon	0.54	4	2	1	oreille	103.51	7	4	2
M	56.26	5.50	3.33	1.33	*M*	50.18	5.17	3.67	1.33