The Role of Spoken and Sign Languages in the Retention of Written Words by Prelingually Deafened Native Signers

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The purpose of this study was to determine the nature and efficiency of the strategies used by prelingually deafened native signers for the temporary retention of written words with reference to a primary language-coding hypothesis (M. A. Shand, 1982). For the gathering of the data, participants were shown lists of serially presented written target words that they were asked to recognize according to their presentation order from within word pools that contained different types of code-specific distracter words. Three performance dimensions were examined: (a) false recognition of target words, (b) correct recognition of target words, and (c) retention of target word presentation order. Participants were prelingually deafened native signers \( (n = 11, \text{average grade level } = 8.18 \pm 1.17) \) and a hearing control group \( (n = 25, \text{average grade level } = 9.00 \pm 0.76) \). Findings from the analysis of the nature of false recognition and the number of correctly recognized words show convincingly that formationally similar distracter words interfered with the memory performance of the native signers and phonologically similar distracter words with that of the hearing control group. It was concluded that the participants decoded written words into a code reflecting their primary language experience for their temporary retention in working memory.

The question of how prelingual deafness effects cognition has been a topic of dispute for over a century (for a review, see Branson & Miller, 2002). An area that has attracted particular attention in this regard is the way prelingual deafness impacts the retention and processing of information in the working memory (WM). This is not surprising because spoken language—through processes of phonological storage and rehearsal—is hypothesized to play a central role in the processing of information in WM (Baddeley, 1986, 1990; Baddeley & Hitch, 1974; Conrad, 1964; Hintzman, 1967; Shiffrin, 1999). Profound prelingual hearing loss not only drastically delays the acquisition of spoken language (for a review, see Paul, 2001) but also is very likely to alter the nature and quality of the permanent representation of the spoken language in the mental lexicon (Miller, 1997; see also Campbell & Wright, 1988; Leybaert, 1993; Mayer & Moskos, 1998). This article represents an attempt to clarify the nature and efficiency of the memory codes prelingual deafened individuals use for mediating the processing of written information in WM.

WM Coding in Prelingually Deafened Individuals

Evidence concerning the memory codes individuals with prelingual deafness use for the representation of information in WM reveals a rather complex picture. We find that at least some individuals with prelingual deafness—like hearing individuals—mediate information processing in WM phonologically (Charlier & Leybaert, 2000; LaSasso, Crain, & Leybaert, 2003; Leybaert & Lechat, 2001; Miller, 2002b), but this seems not to be the case for the majority. An impressive number of studies actually suggest that profound, prelingual hearing loss leads to the development of memory strategies that are not rooted in spoken language (e.g., Conrad, 1979; Harris & Moreno, 2004; Olson & Caramazza, 2004; Leybaert & Caramazza, 2004; for a review, see Musselman, 2000). In other words, unlike hearing individuals, who appear consistently to use phonological code for the maintenance of verbalizable information in WM, individuals with prelingual deafness use for this purpose memory strategies that may be different in nature and show less uniformity.

Indeed, findings from different lines of research suggest that primary language experience (oral language or
sign language [Charlier & Leybaert, 2000; LaSasso et al., 2003; Leybaert & Lechat, 2001; Miller, 2002b]), level of education (Hanson & Lichtenstein, 1990), the mode in which information is presented (orally, visually, manually [Hamilton & Holzman, 1989; Krakow & Hanson, 1985]), and the type of information to be retained (spoken words, written words, signs, finger spellings, etc. [Bellugi, Klima, & Siple, 1975; Bellugi & Siple, 1974; Hamilton & Holzman, 1989; Krakow & Hanson, 1985; see also Hanson & Lichtenstein, 1990; Kyle, 1989]) all may alter the nature of the memory code prelingually deafened individuals rely on. Moreover, some evidence has been reported—in particular, with regard to the processing of spoken language—that individuals with prelingual deafness recode words into a WM code that combines information derived from residual hearing, lip configurations encountered in speech reading, visual cues (cued speed) eventually provided for disambiguating phonological information occurring underspecified on the speaker’s lips, finger spelling, and/or exposure to print (Dodd, McIntosh, & Woodhouse, 1998; Harris & Beech, 1998; LaSasso, Crain, & Leybaert, 2003; Padden, 1991). Such multimodal coding actually highlights the ability of the human brain to adapt to a situation where the processing of spoken language has to be achieved in the absence of proper auditory stimulation.

Individuals who are prelingually deaf probably turn to nonphonological WM strategies because their impaired hearing obstructs the early, complete, and profound internalization of spoken language as a phonological phenomenon, leading to a lack of spontaneity and/or automaticity in its use as a WM code. This is most likely to be the case when such individuals grow up in an environment that does not consistently emphasize reliance on spoken language for communication or may even advocate the use of alternative means (different forms of manual communication) for this purpose (Leybaert & Lechat, 2001). It is, however, noteworthy in this regard that in particular hearing parents who communicate with their deaf children manually often fail to provide them with a consistent, fully fledged language model during the critical period of language acquisition (Akamatsu & Musselman, 1998). As a result, the competency of many of these children in the manual mode may actually never reach a native status (Singleton & Supalla, 2003). In other words, such language systems may not become ingrained as a primary memory code that effectively mediates cognitive processes in WM.

The WM Code of Prelingually Deafened Native Signers

Among the prelingually deafened, deaf children of deaf parents who use sign language as a primary mode of communication at home grow up in an exceptional linguistic situation. As they are systematically and consistently exposed to an adult model of sign language from early infancy, it has been hypothesized that such children internalize signs into a native memory code that serves as a vehicle for mediating the retention and processing of information in WM, just as spoken language does for the hearing (Bellugi et al., 1975). The validity of this hypothesis was also tested in this study.

During the past three and a half decades, the role of sign language in the retention and processing of information in WM has become the subject of intensive research. Evidence obtained from such endeavors suggests that the memory code that proficient signers use for the temporary retention of sign language input reflects the basic, formational parameters underlying the production of signs, namely, hand configurations, hand movements, and places of sign articulation relative to the body of the signer. For example, Wilson and Emmorey (2003) asked competent signers to recall lists of American Sign Language signs following a retention interval. Findings obtained from their study indicated that viewing irrelevant sign input (pseudosigns) during a retention interval inserted between sign presentation and sign recall negatively biased the participants’ recall performance. The same pseudosigns, however, were not found to impair recall performance when displayed during a stimulus retention interval to hearing individuals asked to temporarily memorize a series of consecutively presented written word lists. Such evidence not only indicates that sign language mediates the retention of sign input in WM but also suggests that WM is code-modality specific in nature (Wilson & Emmorey, 2003). This latter conclusion is in line with findings showing that individuals
with intact hearing use phonological code for the short-term retention of verbalizable stimuli (e.g., Baddeley, 1990).

The role occupied by sign language in the temporary retention of sign input is also evident from studies designed to reveal the impact of formational between-sign similarity on the recall of consecutively presented signs. Evidence obtained from such studies consistently shows that just as the recall performance in hearing individuals is impaired by phonological between-item similarity (Baddeley, 1986, 1990; Conrad, 1964; Hintzman, 1967), formational between-sign similarity disrupts sign recall for native signers (Bellugi et al., 1975; Hanson, 1982; Wilson & Emmorey, 1997; Wilson, Emmorey, & Iverson, 2003). However, findings from this line of research also indicate that, notwithstanding their reliance on a sign-based memory strategy, the ability of such individuals to retain information in WM remains notably impoverished in comparison with their phonologically coding hearing counterparts. In view of such inferiority, one may conclude that sign code may be less effective than spoken code in mediating the processing of information in WM (Hanson, 1991; Perfetti & Sandak, 2000).

The Role of Sign Language in the Processing of Written Words

Among the prelingually deafened population, native signing individuals have frequently been found to have superior reading skills (Weisel, 1984; see also Kampfe & Turecheck, 1987; Zwiebel, 1987; for a review, see Paul, 2001). Thus, one would like to know whether such superiority reflects a direct contribution of sign language to the processing of print. This question seems to have particular relevance given that—in alphabetic orthographies—graphemes, the basic orthographic units of text, map on to phonemes (the building blocks of spoken language) but not to the basic formational parameters underlying the production of signs. It may therefore be that sign language fails to sustain the processing of words written in an alphabetic orthography even in instances where it has become internalized as a primary memory code. Regrettably, the little evidence we have about the nature and efficiency of the memory code native signers use for the processing of written words is largely controversial (Kyle, 1989), although at least some of it has been criticized on methodological grounds.

For example, Shand (1982) has launched a primary language-coding hypothesis based on short-term memory experiment that manipulated the phonological and formational similarity in stimulus sequences presented either in sign language (sign sequences comprised formationally dissimilar signs that had phonologically similar paralleling words and visa versa) or in print (sequences of printed words built from words that were phonologically dissimilar but had formationally similar paralleling signs and visa versa). A sample of proficient signers with congenital deafness were asked to recall the sign sequences, the sequences of printed words, as well as control sequences in both conditions in the order the items of each sequence were presented. Analyses showed that recall accuracy was notably reduced by formational between-item similarity but not by phonological between-item similarity. Shand interpreted this pattern as evidence that the memory code his participants used for the temporary retention of signs and written words was sensitive to the formational components of signs. However, Hanson and Lichtenstein (1990), who replicated the Shand study with a sample of hearing university students, found that the recall accuracy of such individuals for lists defined as formationally similar was reduced relative to control lists, as it was for the prelingually deafened signing students tested by Shand. As the former were not familiar with sign language, one necessarily concludes that, whatever caused this negative bias, it was not directly related to the formational properties of the signs paralleling the words. Moreover, it cannot be ruled out that the very same cause was also responsible for the reduced recall found for the signing individuals. This means that the findings from the Shand study cannot serve as supportive evidence for the validity of a primary language-coding hypothesis.

Some support for the validity of a primary language-coding hypothesis, however, has come from studies where the serial recall of lists of consecutively presented written words by native signing individuals was significantly better when the words had existing sign equivalents (Bonvillian, 1983; Bonvillian, Rea, Orlansky, & Slade, 1987; Siedlecki, Votaw, Bonvillian, & Jordan,
Moreover, second-generation signing deaf readers—but not hearing controls—were found to manifest increased error rates in rejecting printed sentences as grammatically incorrect when the paralleling sign of the word creating the grammatical flaw was formationally similar with a sign paralleling a word that (when used) would have been grammatically correct (Treiman & Hirsh-Pasek, 1983). In the same study, manipulating the word creating the grammatical flaw on a phonological dimension (providing a grammatically incorrect word that was homophonous with a word that would have been grammatically correct) biased the accuracy of grammatical judgments for hearing individuals but not for their native signing counterparts. There was also no evidence suggesting that signing individuals referenced other types of information (articulation, finger spelling) when processing the grammaticality of the test sentences.

When taken together, the above findings lend some credibility to the hypothesis that sign language provides native signers with a general memory code that mediates their processing of information, including written words, in WM. However, there is also evidence that challenges the validity of such a primary language-coding hypothesis. For example, it has been demonstrated that when native signing university students were asked to recall serially displayed written word lists, their recall profile reflected sensitivity to the existence of phonological similarity between the presented items but not to that of formational similarity between the items paralleling signs (e.g., Hanson, 1982; Hanson, Liberman & Shankweiler, 1984; Hanson & Lichtenstein, 1990; Krakow & Hanson, 1985). Moreover, a similar sensitivity of native signers to the phonological properties of written words has also been found in a study where judging the semantic acceptability of tongue twister sentences was compared with that of control sentences (Hanson, Goodell, & Perfetti, 1991).

At a first glance, evidence yielded in these studies contradicts the validity of a primary language-coding hypothesis (Shand, 1982). However, some caution is called for before taking this conclusion too far. This is because such evidence was obtained by and large from well-educated prelingually deafened university students, a population that may have developed reading strategies that are not representative of native signers as a whole. Drawing this conclusion seems also justified given an abundant number of findings that suggest that phonological coding may not be a default strategy for the prelingually deafened (Miller, 2006, in press-a, in press-b; for a review of such evidence, see Musselman, 2000). An exception in this regard may be individuals raised according to an educational philosophy that persistently focuses the attention of the prelingually deafened child on the phonological components of spoken language (Charlier & Leybaert, 2000; LaSasso et al., 2003; Leybaert & Lechat, 2001; Miller, 2002b). Because deaf parents of deaf children are not very likely to advocate such an oral philosophy, it is unlikely that, of all prelingually deafened individuals, those who are native signers would especially rely on a phonological memory strategy.

In sum, there appears to be rather broad consensus now that prelingual deafness creates conditions that—in the absence of a massive, preventive intervention—lead to a spontaneous development of nonphonological WM strategies sustaining the mediation of information processing. There also appears to be an agreement that in prelingually deafened individuals for whom sign language is the primary code, this memory code reflects the formational parameters of sign language. However, it has not been firmly established so far whether this code is directly involved in the temporary retention of written words during their processing (Kyle, 1989). Moreover, it is still unclear whether the observed short-term memory weakness of prelingually deafened native signers reflects an inherent deficiency of their reliance on a sign-based memory strategy or is the result of a code incompatibility (Flaherty & Moran, 2004). The study reported here represents another effort to provide answers to these still open questions.

Research Questions

Knowledge concerning the nature and efficiency of the memory strategies prelingually deafened native signers use for mediating the processing of written words in WM is still incomplete. This study aimed to fill in part of this lacuna with findings obtained from a newly designed research paradigm (see below). It addressed the following two specific research questions: Do
prelingually deafened native signers recode written words into a sign-based memory code for their temporary retention in WM? And if so, what are the consequences of using a sign-based memory code for the temporary retention of written words?

Potential Limits of the Classical Research Paradigm

So far, most of the evidence regarding the memory strategies used by the prelingually deafened for the temporary retention of written words has been drawn from experiments comparing the serial recall for visually presented word lists containing items that are similar on a particular (phonological, orthographic, formational, visual, etc.) dimension with recall from word lists containing items that were dissimilar in this regard. Poorer recall performance on the former was taken as evidence that the memory code the individual was using was sensitive to the particular between-item similarity. This method has proven fruitful in unveiling the nature of the memory code that hearing individuals—and maybe also deaf individuals—rely on for the temporary retention of information. But some of its inherent features make it difficult to unequivocally interpret findings obtained from this method, especially when it is used with prelingually deafened individuals.

First of all, it is extremely difficult to create lists of items that will be similar on a particular dimension only, that is, without sharing also other similarities. For example, in the Shand (1982) study, formationally similar items turned out to be partly semantically related as well. Second, word frequency values used for equating the familiarity of the vocabulary included in test word lists and control word lists may not adequately represent readers with prelingual deafness as their reading experience most certainly deviates considerably from that of the average hearing reader. This method has proven fruitful in unveiling the nature of the memory code that hearing individuals—and maybe also deaf individuals—rely on for the temporary retention of information. But some of its inherent features make it difficult to unequivocally interpret findings obtained from this method, especially when it is used with prelingually deafened individuals.

A Preliminary Outlay of the New Research Paradigm

This article uses a research paradigm that was specifically designed to reveal the nature of the WM codes of the two participant groups in a way that avoids interference on memory performance due to differences in their structural knowledge in the spoken code. Therefore, it presented the participants with sequences of single target words, unrelated syntactically as much as possible, with the items of each sequence displayed seriatim on a computer display. Immediately following their presentation, participants were given a test sheet showing a larger word pool that included the previously presented target items. Their task was to indicate the targets by assigning them numbers corresponding to their presentation order. The paradigm was administered to two participant groups, a group of prelingually deafened native signers and a hearing control group.

A word pool used for testing the retention of a particular word sequence comprised two categories of words: the target words the participants had seen on the computer display and a larger set of distracter words that had not been presented previously. In general, the distracter words had no shared semantic, categorical, or linguistic features with the target words, hence were not coding-modality-specific distracter (NCSD) words. A minority among them, however,
resembled the target words on a particular dimension (i.e., were phonological similar, formationally [sign] similar, visually similar). It was the presence of such coding-modality-specific distracter (CSD) words that was assumed to reveal the nature of the memory strategies used by the participants for keeping the target words active while recognizing and numbering them within a given word pool.

The experimental paradigm used benefited from at least three novel approaches. First, knowing in advance that one is expected to recall words in written form or as signs may trigger the reliance on memory strategies that individuals normally would not make use of for mediating the processing of such words in WM. In this study, the initial perception of the stimuli during stimuli presentation and their later recognition within the test matrix both relied on reading. This actually precludes the possibility of the nature of the required mode of recall biasing the nature of the memory strategy the participants used. Second, the nature of the memory strategy of the participants is not inferred from between-stimuli similarity within a target word list but from between-stimuli similarity between specific items from the target word lists and specific items occurring in the word pool used for testing their retention. This increases control with regard to the effect cause by a particular between-stimuli similarity because the nature of this effect becomes directly observable.

Third, and probably most important, the paradigm reveals the nature of the memory code both as a within-condition effect (the number of false recognitions of CSD words vs. NCSD words within a particular condition) and as a between-condition effect (the number of false recognitions of CSD words under different conditions). Given these strengths, evidence obtained from this paradigm should provide of particular credibility for substantiating the validity of hypotheses regarding the nature and quality of the memory codes used by prelingually deafened native signers and hearing individuals.

Hypotheses

This study tested several hypotheses related directly to the two main research questions. A more general hypothesis predicted that the presence of CSD words would negatively impact the ordered recognition of the target words in a word pool. Such interference, however, was anticipated to occur only when the memory strategy used by an individual for holding information in WM proves sensitive to the resemblance between CSD words and target words.

Four specific hypotheses were tested for corroborating the validity of the primary language-coding hypothesis formulated by Shand (1982). The first of these hypotheses stated that the presence of CSD words that rhyme with target words (phonological foil similarity) would be detrimental to the WM performance of hearing individuals but not that of native signers. The second hypothesis predicted that the presence of CSD words with paralleling signs that formationally resemble the paralleling signs of the target words (formational foil similarity) would lead to reduced WM performance in native signers but not in hearing individuals. The third hypothesis forecasted that if—for their processing in WM—individuals indeed recode written words into a memory code extracted from their primary language, visual similarity between CSD words and target words should not be found to impair the WM performance of the two participant groups. Finally, the fourth hypothesis argued that the WM performance of the participants should be notably better in a control condition not comprising CSD words, in comparison to any of the three experimental conditions containing CSD words given that their memory code is sensitive to the resemblance of such CSD words with target words.

Another general assumption of this study was that sensitivity to phonological, formational, or visual resemblance between target words and CSD words would be become manifest in (a) the incidence rate of incorrectly recognized target words (i.e., the assignment of a number to a word within a word pool that is not a target word), (b) the number of correctly recognized target words, and (c) the ability to retain the presentation order of the target words. In line with this assumption, it was hypothesized that foil similarity between CSD words and target words that is detected by the memory code of the participants would lead to (a) an increase in the incidence of recognition errors, (b) a decrease in the number of correctly
recognized target words, and (c) a lower accuracy in the retention of the presentation order of the target words (as indicated by their numeration).

With regard to the impact of foil similarity, we predicted that formational foil similarity between the signs paralleling CSD words and those paralleling the target words would impact the WM performance of the signing participants but not that of the hearing participants. With regard to phonological foil similarity between the CSD words and the target words, however, the WM performance of the hearing participants but not that of the signing participants was expected to be negatively biased. In all, it was predicted that sensitivity to foil similarity would disproportionately increase the incidence rate of incorrectly recognized CSD words relative to the incidence rate of incorrectly recognized NCSD words, thus providing direct evidence for the nature of the memory strategies used by the different participants.

Finally, in line with a position that considers sign code to be less effective for the processing of written words in WM (Hanson, 1991), it was predicted that—relative to hearing participants—native signing participants would be weaker at retaining the target words, a weakness that would be reflected in a smaller number of correctly recognized target words as well as in a reduced accuracy in retaining word presentation order.

Method

Participants

The experiment was administered to 11 native signing students with prelingual deafness and a control group of 25 hearing students. According to their personal files, all participants had intelligence quotients within the range accepted as normal for that age. Moreover, all of them had either intact or corrected-to-normal vision. None of them were diagnosed as having a specific learning disability. None of them were forced to repeat a school year. For all of them, Hebrew was the first spoken language at home and at school.

Deaf participants. Participants included in this group were selected according to five criteria: (a) their hearing loss measured at the frequencies 0.5, 1.0, and 2.0 kHz was 85 dBHL re American National Standards Institute (ANSI, 1989) or higher re ANSI (1989); (b) their deafness was congenital (hereditary); (c) both their parents were deaf; (d) their primary language was Israeli Sign Language (ISL); and (e) they came from families using Hebrew as the first spoken language.

The signer group comprised five boys and six girls and—due to the low prevalence of hereditary deafness—included individuals from different schools and from several grade levels, namely, four were 7th graders, three were 8th graders, two were 9th graders, and two were 10th graders. According to their personal files, none of them had been obliged to repeat a class. The average grade level of the deaf group was 8.18 (1.17) with a mean chronological age of 14.00 years (range 12.4–16.6).

Three individuals from the signer group, one of the 7th graders and two of the 10th graders, were fully mainstreamed into regular hearing classes. The others visited classes for the deaf where instruction was based on a communication philosophy that advocated the simultaneous use of spoken Hebrew and signed Hebrew. All the individuals visiting deaf classes were partly mainstreamed into hearing classes during activities such as arts and sport, and some of them were mainstreamed also in mathematics. According to teacher ratings, the vast majority of them had reading comprehension skills well below those of age-matched hearing students.

In addition to participant information gathered from their personal files and their teachers, information regarding the functioning of the participants in some reading-related domains was available from their participation in several parallel experiments. One of these domains refers to their phonemic awareness and another to their phonological decoding skills. Findings obtained from the experiment assessing phonemic awareness (Miller, in press-b) show that the performance of the signer group in this regard proved to be very poor, relative both to the test scale (5.73 [2.19] on a 12-point scale) and to the phonemic awareness of the participants from the hearing control group (5.73 [2.19] vs. 11.60 [0.71]). A similar weakness was also found in relation to their phonological decoding skills tested in a procedure that asked them to
categorize pseudohomophones (Miller, 2006). As for phonemic awareness, the weakness of the signer group was rather striking relative both to the maximum test score (8.82 [7.13] correct categorizations out of 30) and to the scoring of the participants from the hearing control group (8.82 [7.13] vs. 26.92 [2.53]).

**Hearing participants.** Seven 8th graders, eleven 9th graders, and seven 10th graders were selected from classes paralleling those of the individuals in the deaf group. Thirteen of them were boys and 12 were girls. Only individuals with intact reading skills were included. For all of them, spoken Hebrew was the mother tongue. The average grade level in the control group was 9.00 (0.76) with a mean chronological age of 14.11 years² (range 13.6–16.5).

**Stimuli**

The present experiment tested the nature and efficiency of the memory strategies used by the participants for the temporary retention of written words under four different conditions: (a) a phonological condition designed to track reliance on a phonological memory strategy, (b) a formational condition designed to track reliance on a memory strategy rooted in sign language, (c) a visual condition designed to track reliance on a perception-based memory strategy, and (d) a control condition. In each condition, testing the reliance on a particular memory strategy was examined by asking the participants to remember a sequence of six target words presented one after another on a computer display and to recognize them correctly from within a larger word pool immediately following their representation. Each condition was tested with five word lists.

For each word list, a word pool of 16 words was prepared for testing the abilities of the participants to recognize the six previously displayed target words according to their presentation order. All words were used only once. They were all familiar Hebrew words, which three teachers of the deaf confirmed as being in the active vocabulary of prelingually deafened individuals much younger than those tested in the present experiment. For experimentation, all the words were presented in unpointed Hebrew.⁵ Omitting pointing in Hebrew often leads to homography, so we made sure the vocabulary included no homographs. All items used had available paralleling signs. For explanation and practice, two separate word lists were prepared.

The items of each word pool were presented within 16 quadratic fields arranged in four rows (4 × 4 test matrix) printed on an A4 sheet, each field containing one item (see Appendix A). Each word pool always comprised the six target words of the corresponding word list and 10 not previously presented words that functioned as distracter words. Except in the control condition, the 10 distracter words of a word pool always comprised three CSD (code-specific distracter) words that resembled three of the target words on a particular coding-modality-related dimension but differed from them as much as possible in all other respects. The remaining seven distracter words were NCSD (none code-specific distracter) words that differed from the target words on all relevant (visual, orthographic, phonological, formational, semantic) dimensions. The presentation of each CSD word within the test matrix appeared either above, below, or beside the corresponding target word (see Appendices A and B). Otherwise, the distribution of both target and distracter words within the test matrix was arbitrary.

Using of an unequal number of CSD and NCSD words was intended to help predict their proportional representation among distracter words mistakenly recognized as target words (recognition errors). It was assumed that if recognition errors are arbitrary in nature, then individuals should mistake NCSD words for target words more than twice as often (2/3) than CSD words. If, however, the recognition errors reflect interference from a code-specific resemblance between target words and CSD words, we should then expect the incidence of wrongly recognized CSD words to be notably higher than predicted by their proportional representation among the distracter words.

**Preparation of the stimuli of the phonological condition.** In the phonological condition, the 80 words used as stimuli (five target word sets and five test word pools) were either nouns or adjectives. All 16 words used for building a list of target words and the corresponding test word pool were chosen so they would be semantically unrelated as well as visually
and orthographically distinct and their paralleling signs would not be formationally similar. Except six words—three target words and their corresponding (rhyming) CSD words—the words in a word pool to be used in the phonological condition were also phonologically unrelated.

The preparation of the five word pools to be used in the phonological condition included three basic steps. In Step 1, 15 rhyming word pairs—each pair comprising a target word and its corresponding CSD word—were identified. In Step 2, the 15 word pairs were randomly but equally distributed into five sets, each set containing three word pairs providing the basis for the creation of a target word list and its corresponding word pool. In Step 3, according to the criteria already mentioned, each of the sets was complemented with 10 additional words—three target words and seven NSCD words.

To prevent the rhyme between a target word and its corresponding CSD word from showing up at the orthographic level, we took advantage of two features that are particular to Hebrew orthography. First, Hebrew orthography has some letter graphemes that are homophonic in nature. For example, the letter graphemes ‘‘ת’’ (taf) in the word ‘‘תורה’’ and ‘‘ט’’ (tet) in the word ‘‘תות’’ are both read as the phoneme /t/. Second, in some instances, the phonetic value of certain Hebrew letter graphemes is determined by vowel diacritics rather than by the grapheme per se. For example, the letter graphemes ‘‘א’’ (Ayin) in the word ‘‘מאדא’’ (mada) and the letter grapheme ‘‘ה’’ (hey) in the word ‘‘גדה’’ (gada) have both the phonetic value /a/ that they received from the vowel diacritic ‘‘ך’’ (patach).

Yet, when such letters appear in unpointed Hebrew (‘‘מאדא’’ and ‘‘גדה’’, vowel diacritics omitted), their phonetic identicalness is no longer detectable at the graphemic level. It was by matching words in this way that in the phonological condition rhymes between the target words and CSD words were not reflected at the graphemic level (see Appendix B). If such rhymes still impact short-term memory performance, one logically must assume that this is because to retain them the participants decoded the words phonologically.

Preparation of the stimuli of the formational condition. As in the phonological condition, the preparation of the five target word sets and their corresponding test word pools used in the formational condition was based on a set of 80 familiar Hebrew words—nouns and adjectives. Although the steps underlying the preparation of the stimuli materials were basically the same, there were some essential differences between the two conditions.

First, the 16 words used for building a list of target words and the corresponding test word pool were always chosen to be semantically unrelated as well as visually, orthographically, and phonologically distinct (see Appendix B). Second, the words in a word pool were also unrelated with regard to the formational properties of their paralleling signs, except of course the three target words and their corresponding (formational similar) CSD words.

In word pairs characterized by formational foil similarity, the paralleling signs of the target word and the CSD word were always identical in two of the three formational parameters (hand configuration, hand movement, and places of sign articulation relative to the body of the signer) considered to be the basic linguistic components of sign language (Stokoe, 2005). For example, in ISL, the sign for “SHAME” (busha) and the sign for “WHITE” (lavan) are produced with a different hand configuration but are identical with regard to the hand movement as well as to the place of their execution relative to the body of the signer. In contrast, the sign for “YELLOW” (tsahov) and the sign for “PLANE” (matos) are produced with a different hand movement but are identical with regard to hand configuration and place of sign articulation. If such formational similarity between target words and their corresponding CSD words paralleling signs impact WM performance, it must logically be assumed that it did so because the participants recoded the written stimuli into a sign-based memory code for their temporary retention.

Preparation of the stimuli of the visual condition. In the visual condition, the 80 familiar Hebrew words used for the preparation of the five target word sets and their corresponding test word pools—nouns and adjectives—were semantically, orthographically, phonologically, and formationally unrelated. The essential difference between this and the other conditions was that within each word pool three of the target words
and their corresponding CSD words were similar with regard to their visual overall appearance (visual similar). Such between-stimuli similarity was created by pairing words composed of different letters that, notwithstanding such orthographic disparity, had a very similar overall visual pattern (e.g., נזק - 彩). It was assumed that if such visual (not orthographic) similarity between target words and their corresponding CSD words has a bias on WM performance, it does so because the participants retained the written stimuli in a form that preserved their visual properties (e.g., Conrad, 1979). Indeed, readers with diagnosed dyslexia tested with the same paradigm (see Miller & Kupperman, 2006) proved to be highly sensitive to such perceptual (visual) between-stimuli similarity, whereas their sensitivity to phonological between-stimuli similarity (phonological condition) proved to be very poor.

Preparation of the stimuli of the control condition. As the three experimental conditions, the control condition was built from a pool of 80 familiar Hebrew words (nouns and adjectives) divided into five subsets creating the five target word lists and their corresponding word pools used for testing retention. However, unlike the three experimental conditions, in the control condition, no CSD words were introduced into the test word pools, that is, distracter words differed from target words semantically, phonologically, formationally, visually, and orthographically. Distracter words in this condition—because they do not exhibit a codespecific similarity to the target words—should logically have no differential impact on the ability of the two participant groups to indicate the target words according to their presentation order within their corresponding word pools.

Procedure

All participants were tested in the school they attended and were given time off from their classes for the experiment. The experiment was conducted in a quiet room located on the school grounds. All the instructions regarding the experimental procedure were read out to them by the experimenter. For the signing participants, a professional sign language interpreter translated the instruction simultaneously into ISL. A laptop computer placed on an empty table was used for presenting the target word lists. To make sure there would be enough space on the table for the sheets with the test matrices, the computer was positioned slightly toward the center of the table.

The six target words were presented within a rectangular fixation frame in the middle of the computer screen. All words of each word list appeared in a fixed order, with each word being presented for two seconds followed by a blank interstimulus presentation interval of 1 s. Pacing the presentation of the different lists of a particular experimental condition was experimenter controlled. The presentation of the first item of a target word list was preceded by “####” appearing within the fixation frame. The experimenter started stimuli presentation only after the participants indicated their readiness. The appearance of an asterisk string (***** ) within the fixation frame indicated the end of a displayed word list.

The experiment included two phases, an explanation and practice phase and an experimental phase, both carried out by a research assistant. Participants were told that the experiment was not an examination but was meant to gauge how good children were at remembering words. For task explanation and practice, the experimenter then invited the participants to sit in front of the computer and told them to concentrate on the fixation frame where a series of words would be displayed one after another. She told them that an asterisk string would indicate the end of the presentation and would serve as the sign for them to look for the target words within the practice matrix (the experimenter put the first practice matrix on the table) and to number them with a pencil according to their presentation order. Participants were then given a pencil and asked whether they were ready to try. After they confirmed their readiness, the experimenter started the display of the first practice list and verified proper task understanding by testing the way the participants numbered the items. None of the participants showed any problem in understanding the task requirements. After this understanding was corroborated in a second try, the experimenter moved on to the experimental phase.

The 20 word lists—five lists from each of the four experimental conditions—were mixed and administered
to the participants in four equal blocks. To counterbalance effects from practice and fatigue, the administration order of the four blocks was rotated (i.e., it was repeated with every fifth participant). Between two blocks, a recreation break of 1–2 min was introduced to counteract lack of motivation. During these breaks, the experimenter asked the participants about their favorite activities.

Before presenting the first target word list the experimenter informed the participants that the procedure in the experimental part was principally identical with the one just practiced. She reemphasized to the participants that it was important to remember and indicate the words in the order they had just seen them. This reminder was reiterated at the beginning of each block. The experimenter further told the participants that the sheets with the test matrices would now be placed on the table, covered with an empty sheet that the experimenter would remove the moment the appearance of the asterisks indicated the end of a presentation. The experiment was executed after the participants confirmed that they were ready. The time for indicating the target words in a test matrix was not limited.

Results

The data collected in the present experiment were analyzed in five steps. The goal of the first step was to reveal the nature of the memory-coding strategy that signing individuals and hearing individuals use for the temporary retention of written words based on a thorough examination of the incidence rates of CSD word- and NCSD word-related recognition errors. The analyses performed in the second step were planned to reveal differences in the ability of the two participant groups to retain the written stimuli presented in the different experimental conditions. The third step focused on the ability of the participants to retain the serial order in which the target words had appeared. The fourth step, conducted to give a broader basis to our interpretation of the findings obtained in Steps 1 and 2, aimed to examine correlations between the different performance dimensions. The impetus for conducting the fifth and final step of analyses was to complement quantitative comparative findings with a systematically organized, qualitative presentation of the WM performance of the different individuals of each participant group in those experimental conditions hypothesized to track the nature of their memory codes.

Because the population our study is concerned with makes up only a small part of the overall population, the number of the native signing individuals we were able to test turned out to be relatively small and very different in size from that of the hearing control group. Therefore, to strengthen the reliability of the findings from this study, all analyses were executed in both parametric and nonparametric statistics. To avoid unnecessary overlapping within the Results section, however, it was decided that findings yielded by nonparametric statistics would be reported only in instances where they conflict with findings obtained from parametric analyses or where their presentation is helpful in backing up borderline findings.

Analysis of Recognition Errors in Relation to CSD and NCSD Words and Overall

As mentioned earlier, the proportion of CSD words to NCSD words in a word pool presented on a test matrix was three to seven (see Appendices A and B). To compensate for possible variance between the prevalence of CSD and NCSD recognition errors originating from this disproportional representation, the incidence rate of CSD recognition errors was corrected by multiplying it by the factor 2.33. This correction extrapolates the proportional impact the presence of CSD words had on variance in the occurrence of recognition errors in three experimental conditions. In the following, all analyses comparing the incidence of NCSD recognition errors with the incidence of CSD recognition errors were executed based on the corrected CSD error rates (CSD-c).

As stated, recognition errors serve in this study to help clarify the nature of the WM strategies used by the two participant groups. They were examined by means of two comparison analyses, one that examined the incidence of CSD recognition errors and NCSD recognition errors in the three experimental conditions and another comparing the overall recognition error rate for each experimental condition with that
of a control condition. The analyses comparing the incidence rates of recognition errors originating from confusion between target words and CSD words with those of recognition errors originating from confusion between target words and NCSD words were planned to reveal differences between these two error types within each experimental condition (phonological, formational, visual) and beyond the different experimental conditions (phonological vs. formational vs. visual). The analysis was implemented by means of multivariate analysis of variance (MANOVA) computing group (signers, hearing) as the between-subject factor and distracter word type (NCSD, CSD-c) and test condition (phonological, visual, sign) as two within-subject factors. Averages for CSD-c and NCSD recognition error rates in the different experimental conditions are presented in Table 1.

The “group” effect proved statistically not significant, suggesting that the overall rate of recognition errors was similar for the two groups. The main effect originating from the between-subject factor “distracter word type” was highly significant ($F(1, 34) = 97.11, p < .01$), indicating that, overall, CSD words were proportionally more often mistaken for target words than NCSD words (see Table 1). A close to zero interaction ($F(1, 34) < 0.01$) between the distracter word type effect and the group effect further suggested that this was true for both participant groups (see Table 1). The main effect produced by the between-subject factor “test condition” was also highly marked ($F(1, 34) = 92.15, p < .01$), indicating the existence of considerable variance with regard to the incidence of recognition errors in the three experimental conditions (see Table 1). A significant interaction between the group effect and the test condition effect ($F(1, 34) = 64.70, p < .01$) further suggested that this pattern of variance differed for the two participant groups (see Table 1). Finally, a significant interaction between the test condition effect and the distracter word type effect ($F(1, 34) = 80.15, p < .01$) revealed that CSD recognition errors and NCSD recognition errors did not proportionally contribute to the recognition error rates in the three experimental conditions (see Table 1). A highly significant three-way interaction between the two within-subject factor effects and the group effect ($F(1, 34) = 100.84, p < .01$) implied further that the proportional distribution of CSD recognition errors in contrast to NCSD recognition errors in the three experimental conditions was not the same for the two participant groups (see Table 1).

Several post hoc analyses were conducted to further specify the significance of some of the main effects and interactions yielded by MANOVA. The first

Table 1  CSD-c and NCSD error rates for the phonological, formational, and visual conditions

<table>
<thead>
<tr>
<th>Group</th>
<th>Error type</th>
<th>Rate of CSD and NCSD errors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phonological</td>
</tr>
<tr>
<td>Deaf</td>
<td>CSD-c $^a$</td>
<td>3.18 (2.61)</td>
</tr>
<tr>
<td></td>
<td>NCSD $^b$</td>
<td>2.00 (1.79)</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>5.18 (2.77)</td>
</tr>
<tr>
<td>Hearing</td>
<td>CSD-c $^a$</td>
<td>9.60 (1.94)</td>
</tr>
<tr>
<td></td>
<td>NCSD $^b$</td>
<td>1.00 (1.12)</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>10.60 (2.06)</td>
</tr>
<tr>
<td>All</td>
<td>CSD-c $^a$</td>
<td>7.63 (3.68)</td>
</tr>
<tr>
<td></td>
<td>NCSD $^b$</td>
<td>1.31 (1.41)</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>8.94 (3.39)</td>
</tr>
</tbody>
</table>

*Note. Standard deviations for the respective means are shown in parentheses.*

*There were three CSD words and seven NCSD words per test matrix. CSD-c corresponds to the corrected number of CSD recognition errors taking into account the proportional prevalence of CSD words among the distracter words in a test matrix. The value of CSD-c was calculated by multiplying the original CSD error rates by the factor 2.33, the relative proportion of CSD words (three) and NCSD words (seven) within a particular test matrix.*

*NCSD recognition errors represent errors that do not exhibit a particular similarity to the target words. They therefore can be considered as arbitrary.*
of these examinations clarified the final significance of the test condition effect based on a series of planned paired t test procedures comparing the incidence of recognition errors in each of the three experimental conditions (see Table 1). Findings obtained from these analyses suggested that, overall, the incidence of recognition errors was notably higher in the phonological condition than in the formational or the visual condition \((t(35) = 4.26, p < .01); t(35) = 7.54, p < .01, \) respectively. Overall, however, there was no evidence for a similar significant difference between the formational and the visual conditions.

To help clarify the final significance of the interaction between the group effect and the test condition effect, a between-condition recognition error discrepancy measure was calculated for each of the two experimental conditions (phonological—sign, phonological—visual, sign—visual). A group comparison based on one-way analysis of variance revealed notable differences between the two participant groups with respect to all three discrepancy measures \((F(1, 34) = 101.71, p < .01); F(1, 34) = 96.94, p < .01; F(1, 34) = 20.70, p < .01, \) respectively). Particular attention in this regard warrants the inverse nature of the recognition error discrepancy the two groups manifested between the phonological and the formational conditions (see Table 1). It actually indicates that these two conditions biased the memory performance of the two groups in a very different manner.

Of further interest is the significant interaction revealed by MANOVA between the distracter word type effect and the test condition effect. A series of planned paired t tests comparing the size of the CSD/NCSD discrepancy revealed for each of the three experimental conditions indicated that, overall, this discrepancy between the two error types was significantly more prominent in the phonological condition than in the formational condition \((t(35) = 3.36, p < .01)\) and the visual condition \((t(35) = 8.56, p < .01)\), whereas in the formational condition, it was more marked than in the visual condition \((t(35) = 4.02, p < .01)\).

An additional post hoc analysis focused on clarifying the essence of the three-way interaction between the distracter word type, the test condition, and the group effects. For this purpose, two one-way analyses of variance were executed, one comparing the CSD/NCSD recognition error discrepancy the groups exhibited for the three test conditions and another comparing their CSD and NCSD recognition error rates directly. Finding obtained from the analysis of the CSD/NCSD error discrepancy revealed that—in the phonological condition—the hearing control manifested a notably larger CSD/NCSD discrepancy relative to their signing counterparts \((F(1, 34) = 54.53, p < .01)\) due to a rather drastically increased rate of recognition errors originating from the confusion of (phonological) CSD words with target words (see Table 1). A paired t test comparison indeed confirmed that for the hearing group the incidence of CSD recognition errors was significantly higher than the incidence of NCSD recognition errors \((t(35) = 17.87, p < .01)\). No evidence for a similar difference in this regard was found for the signing participants.

The analysis of the CSD/NCSD recognition error discrepancy also revealed a notable group difference with regard to the formational condition \((F(1, 34) = 82.74, p < .01)\). However, unlike in the phonological condition, this difference reflected the fact that the signing participants manifested a markedly increased CSD error rate due to the confusion of target words with formationally similar distracter words (see Table 1). A paired t test comparison confirmed that, in this condition, the incidence of CSD errors exhibited by the signer group was indeed markedly higher than the incidence of NCSD errors \((t(35) = 20.65, p < .01)\). No evidence for a similar difference in this regard was found for the hearing participants. Interestingly, neither was there any evidence that distinguished the two participant groups with regard to the CSD/NCSD recognition error discrepancy they exhibited in the visual condition nor was there statistical evidence that in this condition the incidence of the CSD recognition errors markedly diverged from that of NCSD recognition errors.

The one-way analysis of variance conducted to directly compare the CSD and NCSD recognition error rates of the two groups indicated that—in the phonological condition—the hearing participants manifested a markedly increase CSD recognition error rate in comparison to their signing counterparts \((F(1, 34) = 67.61, p < .01; see Table 1)\). In contrast, in comparison to the hearing participants, the signer group exhibited a significantly higher CSD recognition error rate in
the formational condition ($F(1, 34) = 138.83, p < .01$). There was also some evidence that the signer group made more CSD recognition errors in the visual condition ($F(1, 34) = 5.60, p < .05$). With regard to the incidence of NCSD recognition error, a group difference was found only with regard to the phonological condition ($F(1, 34) = 4.19, p < .05$) where the NCSD recognition error of the signing participants was more emphasized in comparison to the hearing participant.

The second analysis applied to the recognition errors occurring in the memory products of the two participant groups focused on the disclosure of possible quantitative differences between the occurrence of such errors in the three experimental condition, in comparison to their occurrence in a control condition in which word pools used for the identification of the target words contained only NCSD words (no CSD words). Averages for the overall recognition error rates in the different experimental conditions and a control condition are presented in Table 2.

It was hypothesized that the presence of CSD words in the experimental conditions would increase the incidence of recognition errors if the memory code of the participants was sensitive to their similarity to target words. The analysis was based on three paired $t$ test comparisons executed for each group separately. Findings obtained from these comparisons suggested that, for the signing participants, the incidence of recognition errors in the formational condition notably increased compared with the control condition ($t(10) = 2.67, p = .01$). There was no statistical evidence that for this group the recognition error rates of any of the other experimental conditions was notably different from the one exhibited in the control condition. For the hearing control group, the incidence of recognition errors in the phonological condition was markedly higher than for the control condition ($t(24) = 10.41, p < .01$). There was also evidence for a significantly increased recognition error rate in the formational condition relative to the control condition ($t(24) = 2.77, p = .01$). No such variance was found, however, between the visual and the control condition.

One-way analysis of variance was use to directly compare the two groups with regard to the recognition error rates they exhibited in the four test conditions. Findings indicated that the incidence of recognition errors in the phonological condition was notably higher for the hearing participants than for their signing counterparts ($F(1, 34) = 10.95, p < .01$; see Table 2). In contrast, in the formational condition, the signer group exhibited markedly more recognition errors than the hearing control ($F(1, 34) = 142.07, p < .01$). There was no statistically significant evidence that distinguished the recognition error rates of the participant groups in the visual and the control conditions.

**Analysis of the Retention of Target Word**

The analyses performed for revealing quantitative differences in the ability of the two groups to retain the written target words was based on MANOVA comparing the amount of target words the two participant groups correctly recognized in the different conditions. The analysis was conducted with group as a between-subject factor and test condition as a within-subject factor. Group averages as well as averages for the four conditions separately are presented in Table 3.

The group effect yielded by MANOVA was statistically not significant, suggesting that, overall, the two groups were not notably different in their ability to retain and recognize target words presented to them serially from within the test matrices. The main effect produced by the test condition was statistically significant ($F(1, 34) = 42.01, p < .01$), indicating that the amount of correctly recognized items varied notably for the four test conditions. A marked interaction between the group effect and the test condition effect ($F(1, 34) = 25.63, p < .01$) further suggested that the way the different conditions biased the ability of the participants to retain the target words was not uniform for the two groups.

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean recognition error rates</th>
<th>Phonological</th>
<th>Formational</th>
<th>Visual</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deaf</td>
<td>3.36 (1.86)</td>
<td>4.36 (1.96)</td>
<td>3.82 (1.78)</td>
<td>2.64 (2.38)</td>
<td></td>
</tr>
<tr>
<td>Hearing</td>
<td>5.12 (1.27)</td>
<td>1.76 (1.90)</td>
<td>2.60 (1.63)</td>
<td>1.72 (1.86)</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>4.58 (1.66)</td>
<td>2.56 (2.25)</td>
<td>2.97 (1.75)</td>
<td>2.00 (2.04)</td>
<td></td>
</tr>
</tbody>
</table>

*Note. Standard deviations for the respective means are shown in parentheses.*

- The analyses performed for revealing quantitative differences in the ability of the two groups to retain the written target words was based on MANOVA comparing the amount of target words the two participant groups correctly recognized in the different conditions. The analysis was conducted with group as a between-subject factor and test condition as a within-subject factor. Group averages as well as averages for the four conditions separately are presented in Table 3.

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Several post hoc analyses were conducted to clarify the final significance of the test condition effect as well as its interaction with the group effect. A series of *t* test comparisons executed to contrast memory performance in the different test conditions indicated that, overall, recognition of target words in the phonological condition was significantly impoverished relative to all other conditions (formational *t*(35) = −4.31, *p* < .01; visual *t*(35) = −5.31, *p* < .01; control *t*(35) = −6.90, *p* < .01). An examination of the two participant groups separately revealed that, for the hearing group, the amount of correctly recognized items in the phonological condition was markedly impoverished relative to all other experimental conditions (formational *t*(24) = −9.31, *p* < .01; visual *t*(24) = −10.33, *p* < .01; control *t*(24) = −9.96, *p* < .01). Moreover, there was also statistically significant evidence that, for this group, the visual condition caused a reduction in the number of correctly recognized items compared with the formational condition (*t*(24) = −2.62, *p* < .05) and the control condition (*t*(24) = −2.16, *p* < .05). There was, however, no evidence pointing to a difference in this regard between the formational and the control condition. With regard to the signer group, the number of target words correctly recognized by signing individuals in the formational condition was significantly reduced in comparison to the control condition (*t*(10) = −2.23, *p* < .05). A similar tendency of borderline significance (*t*(10) = −1.71, *p* = .06) was also noticeable when we compared their recognition of target words in the formational condition, relative to the phonological condition. There was, however, no statistically significant evidence of different word recognition rates in the formational condition, as opposed to the visual condition.

An additional analysis was conducted to reveal differences between the participant groups in the amount of correctly recognized items under different test conditions. A comparison based on a one-way analysis of variance indicated that, in the phonological condition, the amount of correctly recognized target words by the hearing group was notably smaller than that of the signer group (*F*(1, 34) = 10.59, *p* < .01). On the other hand, the amount of correctly recognized target words in the formational condition was notably reduced for the signer group relative to the hearing control group (*F*(1, 34) = 15.70, *p* < .01).

### Analysis of the Retention of Target Word Presentation Order

Prior to analyses examining differences in the ability of the two groups to retain word presentation order (as reflected in the ordered numbering of the items within a test matrix), order accuracy (OA) was calculated as a percentile measure using the following function: 

\[
OA = \left(1 - \frac{C}{CP} - 1\right) \times 100.
\]

*C* stands for the total number of ordinal errors made by the participant in the ascending numbering of the items, whereas CP − 1 represents the number of ordinal errors possible relative to the number of correctly recognized items. For example, recognizing all six items of a stimulus sequence correctly, making one ordinal error (1 2 4 3 5 6)’ in their numbering, outputs an OA of 80%, whereas making two ordinal errors in the numbering (1 4 2 3 5 6) outputs an OA of 60%. On the other hand, making one ordinal error while recognizing only five of the six items of a stimulus sequence correctly (2 4 3 5 6)’ outputs an OA of 75% or for two ordinal errors (1 4 3 5) an OA of 50%. The mean OA values, overall, and for each experimental condition separately are presented in Table 4.

<table>
<thead>
<tr>
<th>Group</th>
<th>Phonological</th>
<th>Formational</th>
<th>Visual</th>
<th>Control</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deaf</td>
<td>5.30 (0.37)</td>
<td>5.09 (0.40)</td>
<td>5.25 (0.36)</td>
<td>5.40 (0.48)</td>
<td>5.26 (0.29)</td>
</tr>
<tr>
<td>Hearing</td>
<td>4.96 (0.26)</td>
<td>5.64 (0.37)</td>
<td>5.48 (0.33)</td>
<td>5.62 (0.40)</td>
<td>5.42 (0.30)</td>
</tr>
<tr>
<td>All</td>
<td>5.06 (0.33)</td>
<td>5.47 (0.46)</td>
<td>5.41 (0.35)</td>
<td>5.55 (0.43)</td>
<td>5.37 (0.37)</td>
</tr>
</tbody>
</table>

*Note.* Standard deviations for the respective means are shown in parentheses.

*aMaximum recall per list = 6.*
MANOVA using group as a between-subject factor and test condition as a within-subject factor. The group effect yielded was statistically significant, suggesting that, overall, the ability of the two groups to retain the serial presentation order of the target words was markedly different ($F(1, 34) = 51.45, p < .01$). In addition, a significant test condition effect revealed that the ability to retain the presentation order of the target words was biased by particularities related to the different test conditions ($F(1, 34) = 13.52, p < .01$). An insignificant interaction between the two main effects suggested further that this bias was rather uniform for the two participant groups.

Several post hoc analyses were executed to further specify the final significance of the two main effects revealed by MANOVA. In the first of these examinations, one-way analysis of variance was conducted to further clarify the group effect by means of a comparison of the ability of two groups to retain target word presentation order in each test condition. Findings pointed to a notable inferiority of the signing participants in these respects with regard to all four test conditions ($F(1, 34) = 19.96, p < .01$; phonological; $F(1, 34) = 23.45, p < .01$; formational; $F(1, 34) = 15.38, p < .01$; visual; $F(1, 34) = 29.42, p < .01$).

A series of paired $t$ test comparisons was conducted to study the way peculiarities of the different test conditions impacted the retention of presentation order. Overall, word presentation order was found to be preserved better in the phonological condition than in the visual condition and the control condition ($t(35) = 3.13, p < .01$; $t(35) = 2.72, p = .01$, respectively). There was no statistical evidence that ability of the participants to retain word presentation in the visual and the control conditions differed notably.

### Examination of Correlations Between the Different Performance Dimensions

This line of analyses focused—in a first step—on elucidating specific correlations between the occurrence of CSD errors and the average number of correctly recognized items overall. Due to the small size of the signer sample, in conjunction with some divergence between results obtained from parametric and non-parametric analyses, it was decided to report the more thorough findings yielded by the latter (Spearman’s rho). There was no statistical evidence that for any of the two groups the number of CSD recognition errors produced in a particular (phonological, formational, visual) condition was indicative of the total number of items correctly recognized by the participants. The same was also true when the overall ability of the groups to retain item presentation order was computed as the correlating variable.

A second series of correlation analyses examined the way NCSD recognition errors correlated with the amount of correctly recognized items and the ability of the groups to retain the item presentation order. For this purpose, the NCSD recognition error rates of the different experimental conditions were averaged. However, for optimizing this average, NCSD error rates from experimental conditions containing CSD words that negatively biased the memory performance of the participants—for the signer group the formational condition and for the hearing control the phonological
condition—were excluded from the averaging procedure. The correlations between these optimized NCSD error averages and the overall amount of correctly recognized items were statistically highly significant for both participant groups (for the signer group $r_s = -0.85, p < .01$, one tailed [$n = 11$]; for the hearing control $r_s = -0.91, p < .01$, one tailed [$n = 25$]). However, there was no statistical evidence that the size of the NCSD error rates was indicative of the ability of the groups to retain the item presentation order. Finally, no significant correlations were found between NCSD recognition error rates and the CSD recognition error rates. This was true overall as well as for each experimental condition separately.

Systematic, Qualitative Representation of the WM Performance of the Groups

Averaging the performance of individuals on a particular performance dimension allows generalization. Regrettably, however, by averaging performance, important information regarding the functioning of the individual is lost and, therefore, is not taken into account in drawing conclusions regarding the final significance of findings obtained from quantitative analyses. Such loss may occasionally lead to overgeneralization or even to misinterpretations of findings. As already stated, the motivation for the fifth step of analyses was to extend quantitative, comparative findings regarding the ability of the two groups to temporarily retain seriatim-presented written words, by the organized presentation of their qualitative memory performance. For the sake of simplicity, this presentation was restricted to the phonological condition and the formational condition that in prior analyses repeatedly proved to unequivocally distinguish between the two participant groups. The presentation was implemented by means of a cross-tab analysis organizing the prevalence of formational and phonological CSD recognition errors made by the individuals of the two participant groups with reference to their ability to retain word presentation order. The result of this qualitative organization is presented in Table 5. For the signing individuals, information regarding their educational placement (fully mainstreamed vs. only partly mainstreamed) is added.

Several noteworthy points relevant for the discussion of findings obtained from comparative analyses in the Discussion section should be highlighted. First of all, the two groups are clearly distinguishable on the dimension of formational as opposed to phonological CSD recognition errors. Second, the two groups are also clearly distinguishable with regard to their ability to retain item presentation order. Third, the two signing individuals with the highest OA measures (96%) were located at the low end on the phonological CSD recognition error dimension. Fourth, the hearing individual with the lowest OA measure (74%) was highest at the phonological CSD recognition error dimension. Finally, in the signer group, at least one of the two individuals who seemed to have been sensitive to the phonological properties of the target words (three CSD recognition errors in the phonological condition) was nevertheless found to have a significantly reduced ability to retain word presentation order (83%) in comparison to the average hearing participant. The same individual was also fully mainstreamed into a hearing class.

Discussion

This study represents an additional attempt to clarify the nature and efficiency of the memory codes used by prelingually deafened native signing individuals and by hearing individuals for the retention of written words in WM. The first and probably most central question in this regard is whether due to the consistent early exposure to sign language individuals internalize sign language as a general memory code that they then make use of for mediating the processing of information in WM. Based on findings obtained in the present experiment by means of an innovative experimental paradigm, the answer to this question is definitely yes. In fact, all the native signing participants tested in the present experiment proved sensitive to formational similarity between signs paralleling the presented written words (see Table 5). This actually sustains the validity of the primary language-coding hypothesis originally formulated by Shand (1982), a hypothesis that has suffered from some serious setbacks during the last two and a half decades (see, e.g., Hanson & Lichtenstein, 1990; Kyle, 1989). It also substantiates the specific research hypotheses tested in this study in relation to this question.
The unambiguousness with which the findings from this study advocate the validity of a primary language-coding hypothesis arises from the fact that the use of a sign-based memory code by the native signer group was reflected in evidence from several sources, the same sources that also provide strong evidence for the use of a phonologically based memory strategy by the hearing individuals. The first and most direct source of evidence is the rather striking, yet predicted, discrepancy between the incidence of CSD recognition errors and NCSD recognition errors in the formalional condition (pinpointed as a within-condition effect; see Table 1). Considering that in this condition the resemblance of CSD recognition errors to the target words was restricted to a resemblance in the formalional parameters of their parralelling signs (e.g., לַבָּן [LAVAN = white] and בִּשְׂרוֹן [BUSHA = shame]), the disproportionally high incidence of such errors found in the products of all signing individuals (see Table 4), as hypothesized, cannot be explained but by postulating the encoding of the written target words into sign code for their temporary retention. The fact that a similar significant coding-modality-related error discrepancy was found for the hearing group in the phonological condition (e.g., גֶּבֶשׁ [GEVES = gypsum] and כְּבָשׁ [KEVES = sheep]) not only demonstrates the appropriateness of the experimental paradigm for revealing differences in the nature of the memory codes the two participant groups relied on for the temporary memorization of written words but also lends

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<tr>
<td></td>
<td>Total number of participants</td>
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</tbody>
</table>

aPercentile word presentation OA.
bFully mainstreamed prelingually deafened signers.
additional credence to the conclusion that the signing individuals must have used for this purpose a code they extracted from their primary language.

A second source of direct evidence for the use of a sign-based memory code by the signer group is the finding of a highly significant difference in the incidence of CSD recognition errors in the formational condition, as opposed to the phonological and the visual conditions (see Table 1). The fact that no such difference was found in analyses comparing the CSD recognition error rates in the phonological condition with that in the visual condition strongly suggests that the outstanding high rate of CSD recognition errors in the formational condition originated, as anticipated, from the nature of their memory code. This conclusion is further supported by the finding of a similar ignorance in hearing individuals to the formational similarity carried by the CSD words in the formational condition and to the visual similarity such words exhibited to target words in the visual condition. Moreover, the finding that no significant association was found between NCSD recognition error rates and CSD recognition error rates for the signer group in the formational condition and for the hearing group in the phonological condition actually suggests that these two types of errors have essentially different roots.

It is noteworthy in this regard that, unlike the hearing individuals who had no sign language knowledge, all individuals in the signing sample definitely had some level of competency in the spoken code. This must have been particularly true for those among them who were fully mainstreamed into hearing classes. The fact that such knowledge apparently was not used by the vast majority of these individuals for sustaining the retention of written words (see Table 5) is rather surprising given that written words definitely map more readily to spoken words than to signs. This actually suggests that once sign language has become a vehicle for thinking, spoken language, even if used quite extensively, remains but a second language.

A third source of evidence suggesting that the two groups used essentially different short-term memory strategies for the temporary retention of the written words is obvious from the comparison of their CSD recognition error rates in the different experimental conditions (formational, phonological, visual). The marked between-group difference yielded in this regard in the formational and phonological conditions is a firm evidence for an interference caused by the nature of their unique memory codes, uniqueness reflected in a specific sensitivity to a particular type of distracter words while at the same time being mostly ignorant of the presence of other types of distracter words. It is, of course, worth noting that—as indicated by statistics—in the visual condition the signer group exhibited, on average, a somewhat higher CSD recognition error rate, hinting to some increased sensitivity to the presence of visual distracter words. Such increased sensitivity on this dimension makes intuitive sense given that for a proper functioning in their surroundings such individuals probably have to visually compensate for their permanent lack of auditory input. On the other hand, one cannot ignore the fact that—for the signing participants—the CSD recognition error rate in the visual condition was only about one third of their CSD recognition error rate in the formational condition and that its size proved to be proportional to the size of the NCSD recognition error rate in the same condition. This later finding actually suggests that the CSD recognition error group difference found in the visual condition may actually not stand for a particular visual sensitivity but may reflect the fact that the signer group in this condition simply made somewhat more arbitrary errors in comparison to their hearing counterparts.

A fourth, yet less direct, source of evidence that permits inferring the use of different memory-coding strategies by the two participant groups is the finding that the amount of correctly recognized items was selectively biased by the presence of different types of CSD words in the different experimental conditions (see Table 3). As predicted, as well as in line with findings reported by other researchers (e.g., Conrad, 1979), for the hearing participants, phonological similarity between CSD words and target words caused notable negative interference with reference to their ability to properly retain and consequently recognize the target words within a test matrix. Such phonological interference was substantiated with regard to both the control condition and the formational and the visual conditions. It is noteworthy in this regard that the latter two conditions—although not designed to
function as such—became control by default for individuals using a memory strategy not sensitive to the competing formational or visual information carried by the CSD words. Therefore, the finding that for the hearing participants the consequences of phonological interference for the retention of written words were notable relative to all other conditions lends additional credence to the conclusion that the memory strategy they used for retaining the written words in the present experiment was phonological in nature. The same conclusion is also warrantable based on the finding that, in the phonological condition, the hearing group recognized significantly fewer items than did their signing counterparts.

Although somewhat less clear-cut than for their hearing counterparts, the success of the signer group in recognizing the target words in the different experimental conditions also indicates that they relied on their primary language for retaining the written target words while numbering them within the test matrices. This conclusion is reasonable in view of the findings that, in the formational condition, the accuracy of the signing participants in recognizing the target words was markedly reduced relative to the control condition and almost significantly reduced in comparison to the phonological condition (see Table 3). Moreover, in the formational condition, the signer group was significantly less successful in this regard compared with the hearing control group, a weakness similar to that demonstrated by the latter in relation to the recognition of the target words in the phonological condition.

Considering the findings presented so far, one cannot escape the impression that the evidence obtained from the present experiment in favor of a primary language-coding hypothesis is remarkably ample and well corroborated through reliance on multiple sources. Whereas in relation to hearing individuals this probably is a mere reaffirmation of a well-known fact, namely, that they have a (natural) propensity for encoding written words into phonological code for their processing in WM (Baddeley, 1986, 1990; Conrad, 1964, 1979; Hintzman, 1967), in relation to native signing individuals our unambiguous findings regarding the use of a sign-based memory strategy touches on a issue for which so far consensus was rather weak (e.g., Kyle, 1989). As stated earlier, an intrinsic question here is how far the reliance on a sign-based memory strategy in the temporary retention of written words alters the efficiency with which such information is retained.

In line with a position that considers sign code to be less effective for the processing of written language in WM (Hanson, 1991), it was predicted that the native signing participants would manifest notably weaker short-term memory skills, in comparison with their hearing counterparts. This hypothesis, however, gained only partial support from the comparison of the two groups on the different performance dimensions. First of all, there was no statistically significant evidence that the signer participants had a generally reduced short-term memory span due to their reliance on a nonphonological memory strategy. In fact, in instances where such decrease became notable (in the formational condition), it seemed to reflect interference from formational CSD words rather than a memory weakness per se. This conclusion is also warranted in view of the finding that a similar memory weakness was observed for the hearing control in instances where the presence of phonological CDS words interfered with the word recognition process. This conclusion is even further underpinned by the finding that for neither group the frequency of occurrence of CSD errors was indicative of their ability to retain and correctly recognize the target words. This actually suggests that whether or not the participants remember the target words was not directly determined by the nature of the memory code they used for sustaining the temporary retention of these words. Indeed, the rather remarkably strong correlation between the amount of correctly recognized target words and the incidence of NCSD errors seems to imply that memory performance in the present experiment reflected a more general ability of the WM of the participants to retain written information temporarily rather than constraints imposed by the nature of the code they used for the preservation of this information.

It is noteworthy that, overall, the native signer group was not distinguishable from the hearing control on the assessed recognition error dimensions (see Table 2), although there were some notable differences in this regard when considering the occurrence of such errors under particular experimental conditions. However, the finding that—except in the formational
condition where sensitivity to formational similarity markedly raised their CSD recognition error rate—the recognition error rates of the signer group was not found to be markedly higher relative to the hearing control necessarily must lead to the conclusion that the use of a sign-based memory code was by and large quite effective for the encoding of written words. Indeed, evidence obtained from a parallel experiment (Miller, 2006) shows that—unlike spoken language—sign language lacks structural properties that can be directly linked to the graphemic components of written words. Given this modality-inherent constraint, it actually may be that the process underlying the encoding of the written words was essentially different for the two participant groups, with the decoding task of the hearing group being sustained by a grapheme-to-phoneme conversion procedure that directly decoded the written words into a form recognized and sustained by their WM code. The fact that no such conversion mechanism is available for connecting written words in such a straightforward manner to signs definitely alters the way words become connected with signs.

Regrettably, findings from this study fail to demonstrate at what point within the word recognition process this connection is made, that is, prelexically or postlexically, although some recent findings argue for the latter (see Miller, in press-a, in press-b). Yet, at whatever point this connection was made, it probably associated between orthographic knowledge, on the one hand, and sign code, on the other hand. Orthographic knowledge, however, may not always be unequivocally internalized in the prelingually deafened reader due to insufficient reading experience. This may explain why the signer group in some instances tended to manifest somewhat higher recognition error rates in comparison with their hearing counterparts. It also would explain why in other studies the short-term memory performance of readers with prelingual deafness was found to be comparable to reading age-matched hearing readers (Harris & Moreno, 2004).

The only performance dimension on which the signer group was clearly distinguishable from the hearing group was the dimension representing their ability to retain the order in which the items of a word list were presented on the computer display. This finding is in line with findings from numerous other studies that have pinpointed a weakness of prelingually deafened individuals in retaining the order in which information is presented (Bellugi and Siple, 1974; Bellugi et al., 1975; Hamilton & Holzman, 1989; Hanson & Lichtenstein, 1990; Krakow & Hanson, 1985; for a review see Padden & Hanson, 2000). Given the solid evidence revealed by the present experiment for the use of a sign-based memory strategy by the signing participants, it is of course tempting to associate the reliance on such a strategy with their markedly impoverished ability to retained word presentation order. This line of interpretation has even greater appeal given the widely accepted standpoint that a phonological memory strategy is particularly suitable for the retention of sequentially encountered information (Baddeley, 1986; Padden & Hanson, 2000; Perfetti & Sandak, 2000). However, several findings from this study suggest that this line of interpretation may not be tenable for explaining the discrepancy in the ability of the two groups to retain word presentation order.

The first source of evidence in this regard is that the retention of word presentation order was not found to be significantly biased by the presence of phonological CSD words (phonological condition). It is in particular for the hearing participants that the presence of such words should have had a negative impact on the ability to retain word order information in relation to this particular condition. It is noteworthy that, as in the case of phonological distracters for the hearing, formational distracters did not lead to an additional reduction in the ability of the signing participants to retain order information. Taken together, these two findings seem to suggest that the retention of word presentation order was not directly linked to the nature of the memory codes used by the participants. This conclusion is further supported by the fact that there was no significant positive association between the frequency of occurrence of CSD recognition errors in the phonological condition—indicative of phonological sensitivity—and the ability of the participants to keep track of the word presentation order. Moreover, variation in the sensitivity of the signing participants to formational similarity
(rate of formational CSD errors) showed no negative correlation of how successful they were in retaining the word presentation order.

Finally, a cross-tab analysis inspecting code sensitivity in relation to success in retaining word presentation order shows (see Table 5) that the two signing individuals with OA scores (96%) above the hearing average were apparently completely ignorant of the phonological properties of the written target words they were required to memorize and of the words in the test matrices among which they were asked to number these target words. Yet, the very same participants manifested a notable sensitivity to the formational components of such words paralleling signs (see Table 5). Together with the other finding reported above, there is the fact that on the word presentation OA dimension they notably outperformed other signing individuals who demonstrated some reliance on phonemic awareness while recognizing the target words. This suggests that drawing a causal link between the apparent difficulty of most of the signing individuals in retaining word presentation order and their use of a sign-based memory strategy may actually not be scientifically defensible.

Turning attention away from sign language as the direct cause for an impoverished ability to retain order information, of course, does not remedy this weakness and future research will be necessary to further help unravel its true cause. Such research is particularly imperative because for the proper mastery of skills like reading and writing it is of central importance to preserve the order in which information is encountered. Some preliminary endeavors going in this direction have indeed shown that regardless of their coding strategy—phonological or not—prelingually deafened individuals demonstrated hearing-comparable short-term memory performance, including the retention of word presentation order, when these groups were asked to recall word lists for which the items could not be chunked readily based on some form of knowledge (Miller, 2002a, 2004).

In summary, evidence obtained from the present short-term experiment strongly suggests that individuals use their primary language as a code for mediating the processing of written words in WM. For prelingually deafened individuals with a native competence in sign language, this memory code seems to reflect formational information extracted from sign language. Although signing individuals manifested a notable difficulty in retaining order information, fine-tuned analyses indicated that this weakness cannot be directly causally linked to their reliance on memory strategy rooted in sign language.

In this study, all signing participants were found to be sensitive to formational similarity between some of the signs paralleling the written words used for stimulation. On the other hand, the vast majority of the same individuals proved strikingly ignorant to phonological resemblance between written words. Whereas such findings convincingly corroborate the conclusion that for such individuals sign language mediates the retention of written words, one cannot overlook the fact that the sample from which this evidence was gathered was rather small in size and its generalizability, therefore, needs to be substantiated further. It also should be emphasized that among prelingually deafened individuals many may not use sign language, and among those who use it, a significant part may not have native competence in it. For determining the final significance of the findings reported in this article, the investigation of the memory strategies such individuals rely on in the processing of written words with a method identical or similar to that used in this study is therefore mandatory. A project targeting this objective is currently being launched by the author.


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</table>

**Example:** Matrix used for testing phonological coding

**Instruction:** Order the words in the order they were presented

Note. During experimentation participants saw only the words presented in bold in the center of each matrix field. All additional information presently occurring serves explanatory purposes only.
Appendix B: Ordered short-term recognition.

<table>
<thead>
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<th>Example: Matrix used for testing formalional coding</th>
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<tbody>
<tr>
<td>[Diagram of matrix with Hebrew and English labels]</td>
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### Notes

1. ISL is the sign language used by the deaf community in Israel. As in American Sign Language, its vocabulary is built systematically according to limited sets of formational parameters, such as hand shape, hand movement, and place of articulation.

2. In Israel, children enter primary school at about the age of 6 years.

3. Signed Hebrew and spoken Hebrew are similar in a limited sense, reflected in a rough matching of sign order to word order. In most other linguistic aspects, there are essential incompatibilities between the two systems, such as an almost complete lack of devices in signed Hebrew to represent the rich morphological structure of spoken Hebrew.

4. Because in Israel no standardized reading comprehension tests are available, the actual reading level of the participants with deafness could not be determined. Estimations in this regard are based on teacher ratings that, albeit subjective, show broad interteacher agreement.

5. In Hebrew, a significant part of the vowel information is not depicted by letters but by small diacritical marks (pointing), placed physically below the letters of a word’s consonantal letter string (e.g., the CVCVC string מַלְאָכָה [ma’alakah] [dog]). Such vowel diacritics, however, are not mandatory for text comprehension, and they are gradually removed from textbooks, beginning with Grade Level 2 and being almost completely omitted from reading materials above Grade Level 3 (e.g., the CCC string הַרְכָּבָה [harkevah] [K-V-L-V] [dog]). For a more detailed description regarding the orthographic features of Hebrew and their use for detecting peculiarities regarding the processing of Hebrew orthography, see Miller (2002a, 2004) and Shimron, 1993.

### References


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