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Brain and Language 87 (2003) 227–240
Brain and Language
www.elsevier.com/locate/b&l

Lateralization effects during semantic and rhyme judgement tasks in deaf and hearing subjects

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Accepted 2 April 2003

Abstract

A visual hemifield experiment investigated hemispheric specialization among hearing children and adults and prelingually, profoundly deaf youngsters who were exposed intensively to Cued Speech (CS). Of interest was whether deaf CS users, who undergo a development of phonology and grammar of the spoken language similar to that of hearing youngsters, would display similar laterality patterns in the processing of written language. Semantic, rhyme, and visual judgement tasks were used. In the visual task no VF advantage was observed. A RVF (left hemisphere) advantage was obtained for both the deaf and the hearing subjects for the semantic task, supporting Neville's claim that the acquisition of competence in the grammar of language is critical in establishing the specialization of the left hemisphere for language. For the rhyme task, however, a RVF advantage was obtained for the hearing subjects, but not for the deaf ones, suggesting that different neural resources are recruited by deaf and hearing subjects. Hearing the sounds of language may be necessary to develop left lateralised processing of rhymes.

Keywords: Cerebral lateralization; Hearing impairment; Phonological processing; Semantic processing; Cued Speech

1. Introduction

Over the last decades, the paradigm of visual hemifield presentation has been successfully employed to investigate the differences between the left and right hemispheres in processing written words and other linguistic stimuli. This paradigm is based on the anatomy of the human visual system. The nerve fibers carrying information about stimuli presented in the right visual hemifield (RVF) project to the visual cortex of the left cerebral hemisphere, while the fibers carrying information about stimuli presented in the left visual hemifield (LVF) project to the visual cortex of the right cerebral hemisphere. Provided that a person is forced to fixate the center of the presentation screen, it is thus possible to present words to the desired hemisphere.

Our interest in the visual hemifield paradigm derives from the information it may provide about lateralization patterns in written word processing by deaf individuals. We ask here whether a group of deaf youngsters who have been exposed to Cued Speech (CS) and who are skilled readers display a left hemisphere advantage in processing semantic and phonological information under conditions in which hearing readers do show such an advantage.

At present, there is no clear empirical evidence of left hemisphere advantage for written word processing by deaf youngsters. Hemifield paradigm studies have shown either a left hemispheric advantage, a right hemispheric advantage, or no hemispheric advantage at all (see Conrad, 1979; D'Hondt, 2001; Gibson, 1988 for reviews). For example, in Sanders, Wright, and Ellis's (1989) study, a RVF (left hemisphere) advantage was obtained for semantic judgment on the part of hearing subjects, while a LVF (right hemisphere) advantage was obtained on the part of profoundly deaf subjects who were exposed to total communication. By contrast, Panou and Sewell (1984) observed a RVF advantage in both hearing and deaf who were native signers, and Wilson (1983) obtained the standard RVF advantage for the hearing subjects, and no VF advantage for deaf

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0093-934X/$ - see front matter
doi:10.1016/S0093-934X(03)00104-4

educated with sign language. In the majority of these studies investigating hemispheric specialization in the deaf, auditory deprivation and linguistic deprivation were confounded (Conrad, 1979; Marcotte & Morere, 1990): deaf subjects' lack of knowledge of the grammar and phonology of the language may explain their abnormal laterality patterns.

Indeed, Neville (1991) hypothesized that the acquisition of competence in the grammar of language, including both phonological and syntactic processing, is important in establishing the specialization of the left hemisphere for language. In her research, deaf subjects who scored well on tests of English grammar and who had good knowledge of English phonology displayed the normal pattern of specialization of the left anterior brain regions during the reading of English, while deaf subjects who have not fully acquired the grammar of English do not display the normal pattern.

We report here the first study of a research program exploring the hemispheric specialization of profoundly, prelinguistically deaf youngsters who were exposed systematically to CS. CS, developed by Cornett (1967), is neither a language nor a manually coded system that uses signs from sign language in English word order. CS is rather a mode of communication for visually conveying traditionally spoken languages at the phonemic level, i.e., the same linguistic level conveyed via speech to hearing individuals. The French form of CS, called Langage Parlé Complété (LPC), uses eight hand shapes corresponding to groups of consonants and five hand placements around the face to convey vowels. Phonemes that are easily distinguishable by speech reading are coded by the same hand shape (e.g., /p/, /d/, /ʒ/) or at the same place (e.g., /i/, /ɔ̃/, /ɑ̃/). Conversely, phonemes that have similar lip shapes are coded with different hand shapes (e.g., /p/, /b/) and places (e.g., /u/, /ɔ̃/). Information given by the cues and information given by speech reading is thus complementary. The different hand placements and hand shapes, combined with the mouth shapes, clearly distinguish the 40-or-so phonemes of French. For example, the six French monosyllabic words /pa/, /ba/, /ma/, /pɑ̃/, /bɑ̃/, and /mɑ̃/ are visually indistinguishable without voice for hearing individuals or without cues to the deaf individuals; however, they are readily differentiated when cued. As CS distinguishes between and among the 40-or-so phonemes and the resulting syllables, cueing also provides access to phonology, morphology, lexical information, and syntactical information for spoken language.

Comparing hemispheric specialization for language processing in youngsters raised with CS with that displayed by normally hearing subjects provides a tool with which to test Neville's hypothesis. Children whose parents use CS to communicate with them from an early age are exposed to a linguistic input that is fully accessible and formal. They undergo a normal development of phonology and grammar of the spoken language (Alegria, Charlier, & Mattys, 1999; Hage, Alegria, & Périer, 1991; Leybaert, 2000; Leybaert, Alegria, Hage, & Charlier, 1998; Leybaert & Charlier, 1996; Leybaert & Lechat, 2001b; Nicholls, 1982; Périer, Charlier, Hage, & Alegria, 1988). Before going further, it is necessary to precise what is meant by "phonology" in the CS-users. Contrary to a still widespread myth, phonological development is not exclusively dependent on the auditory modality because phonological representations do not correspond to surface features of speech. Phonological representations are of an abstract nature, representing the "meaningless primitives out of which meaningful units are formed" (Hanson, 1989, p. 73). Recent studies support the hypothesis that phonological segmental information could be obtained by deaf people through sensorial modalities other than audition, mainly through speech reading (Campbell, 1997; Dodd, 1976). However, phonological information contained in visual speech reading is poorer, scarcer, and less precise than information based on auditory inputs for hearing people because many phonemes have similar labial images or no labial correlates. Deaf children exposed to CS early and intensively, who constitute a minority among the deaf community, constitute an exceptional case, in that they acquire a rich and precise phonological system, allowing them to perform accurately rhyming tasks (Charlier & Leybaert, 2000; La Sasso, Crain, & Leybaert, in press).

In this context, demonstrating that the lateralization pattern displayed by CS users is similar to that displayed by hearing subjects would support Neville's hypothesis. It would also mean that the modality difference is not determinant in the emergence of hemispheric specialisation. On the other hand, if CS users display a different pattern of specialization than hearing subjects, one could conclude that the acquisition of the grammar and phonology of a language is not a sufficient condition to entail left hemisphere specialization for the processing of written language, which could require auditory experience to develop in the usual way. When we state that CS-users develop functionally efficient phonological and metaphonological skills, we are not making a strong claim that they use the same information as that used by hearing people. For the moment, we leave open the question of whether the phonological system of CS users is based more on the visual cues attached to the lexical items, while the phonology acquired by hearing people could be more based on sound (see Leybaert & Lechat, 2001a).

We used a simple paradigm in which subjects determined the relationship between two sequentially presented stimuli: a standard presented in the center of the screen, and a target briefly presented in the left or the right visual field. Three tasks were designed, two of which required linguistic processing. The linguistic tasks tested two abilities (semantic judgement and rhyming judgement) that could be affected differently by early linguistic experience.

In the semantic judgement task, subjects decided whether two sequentially presented written French words belonged to the same semantic category (JUS—THE; *juice—tea*) or not (EAU—CRI; *water—cry*). This task requires the standard word to be held in working memory. The appearance of the target word initiates the search for a semantic category common to the standard and the target. Using this approach, an RVF advantage for semantic judgment tasks concerning written words has been repeatedly demonstrated in hearing subjects (Abernethy & Coney, 1996; Hines, Sawyer, Dura, Gilchrist, & Czerwinski, 1984; Klein & Smith, 1985; Nieto, Hernandez, Gonzalez-Feria, & Barroso, 1990; Urcuioli, Klein, & Day, 1981). Evoked potentials studies have shown that semantic processing is quite stable across different linguistic experiences. Hearing subjects and deaf subjects who were native signers display the same kind of responses to content words when reading sentences, while their responses to function words differ greatly (Neville, Mills, & Lawson, 1992). We thus expected to observe an RVF advantage in both hearing and deaf subjects.

The second linguistic task involved a rhyming judgment. In this task, subjects decided whether two sequentially presented written words rhymed (LIEUE—FEU; *stone—own*) or not (VIEUX—VUE; *dare—free*). This task requires the phonological representation of the standard word to be retrieved and held in working memory, and the rhyme constituent of the standard to be identified. The target word must then undergo similar processing. Finally, the rhyme constituent of the standard must be compared to the rhyme constituent of the target. The rhyme portion was spelt differently in nearly all the pairs, in order to avoid deaf subjects using a common strategy, which consisted that they based their decision on orthographic similarity (see Campbell & Wright, 1990; Charlier & Leybaert, 2000; Hanson & McGarr, 1989). In addition, the orthographic similarity between standard and target was held constant across rhyming and non-rhyming pairs. In hearing subjects, rhyme judgment tasks concerning written words are better accomplished by the left hemisphere (Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001; Rayman & Zaidel, 1991), and induce strongly lateralised responses within the cortical regions located around the Sylvian fissure in the left hemisphere (Démonet et al., 1992, Démonet, Price, Wise, & Frackowiak, 1994). Because the rhyme detection task generates robust responses in the left hemisphere language areas, simple fMRI rhyme detection task has been used to assess hemispheric predominance for language in epileptic patients (Baciu et al., 2001). At present, there is neither behavioral data nor imagery data about deaf people's lateralization pattern in rhyme judgment. Provided that we succeed in matching our deaf subjects to the hearing controls with regard to the ability to make rhyming judgments (see below), two outcomes are possible. A pattern of left hemisphere superiority in both groups would indicate that phonological processing is more effectively performed by the left hemisphere, independently of differences in language modality. In contrast, a different pattern of lateralization in deaf and hearing subjects would indicate that the circuits recruited for rhyme judgement are not the same in the two populations, and that hearing speech may be necessary for the development in the left hemisphere of neural systems involved in the matching of phonological information derived from written words.

The third task involved a visual identity judgement task of letter strings: subjects decided whether two sequentially presented sequences of the same letter were physically the same (Eeee–Eeee) or not (Eeee–eeeE). This task requires the standard sequence to be held in working memory, and compare it to the target. No linguistic processing is required to perform this task, which could involve a similar performance of both hemispheres (Jordan, Patching, & Milner, 2000; Pugh et al., 1996) or even an advantage of the right hemisphere (Brand, VanBekkum, Stumel, & Kroeze, 1983; Marsolek, Kosslyn, & Squire, 1992). No difference between deaf and hearing subjects was expected.

These three tasks were first administered to 11-year-old hearing children and to hearing adults in order to investigate to what extent left hemisphere specialization for semantic and phonological processing was stable across this range of age, reading level, and linguistic competence (see Grossi et al., 2001 for evidence about increasing lateralization of visual language-related processing with increasing age). In a second step, these tasks were administered to a group of deaf CS-users, who were compared to hearing controls, individually matched with the deaf as closely as possible in terms of reading level, sex, age, and linguistic competence.

2. Methods

2.1. Materials

Materials consisted of pairs of stimuli. Each pair was composed of a stimulus presented centrally (hereafter: standard), and a stimulus presented laterally (hereafter: target). Half of the targets were presented in the LVF and the other half in the RVF. In the rhyme and semantic conditions, words were used as stimuli. Standard stimuli varied from 3 to 6 letters, and targets varied from 3 to 5 letters. In the visual condition, all stimuli were composed of 4 letters.

2.1.1. Rhyme task

There were 80 pairs of words in the rhyme task. Half were rhyming and half were not. Each target was paired with another target with the same response but presented in the opposite visual field. For instance, the target FEU (pronounced /fœ/), presented in the LVF and rhyming with the standard LIEUE (pronounced lyoe) was paired with the target JEU (pronounced /ʒœ/), presented in the RVF and rhyming with the standard NOEUD (pronounced /nœ/). The same target was also paired with another target, presented in the same visual field, but for which the response was different. For instance, the target FEU, from our example, was also paired with the target VUE (pronounced /vy/), presented in the LVF and non rhyming with the standard VIEUX (pronounced vjoe). Similarly, JEU (pronounced /ʒœ/) was paired with the target RUE (pronounced /ʀy/), presented in the RVF, and non rhyming with the standard QUEUE (pronounced /kœ/, see Appendix A for the complete stimulus list).

This pairing of words was based on length, frequency and number of letters shared with the standard. There were two measures of frequency. First was the class of frequency of written language use, computed from BRULEX, a database containing approximately 30 000 French words (Content, Mousty, & Radeau, 1990). Second, a subjective frequency in everyday language use was evaluated by 21 judges on a five level scale ranging from very rare (1) to very frequent (5). Targets that were rhyming and targets that were not rhyming with standard, and targets that were presented in the two visual fields were comparable for these two measures of frequency and for the number of letters shared with the standard. Table 1 summarizes this data. To minimize the risk of the participant basing his or her judgement on orthographic similarities, rhyming pairs were orthographically different in all cases but two.

2.1.2. Semantic task

There were 80 pairs of words in the semantic task. For half of the word pairs, the standard and the target shared the same semantic category (e.g., the standard LAPIN [rabbit] and the target RAT [rat] belong to the category of animals). For the other half of pairs, they did not share the same category (e.g., the standard LAIT [milk] and the target COL [collar] do not belong to the same category). The same pairing as in the rhyme task has been used with regard to word length and frequency (see Table 1).

2.1.3. Visual task

There were 60 pairs of four letter strings in the visual task. All pairs consisted of the same letters. Three different letters were used (i.e., A, E, and R). In half of the pairs, the standard was identical in case variation to the target (e.g., the standard "Aaaa" followed by the target "Aaaa"). In the other half, the standard and target differed (e.g., the standard "Eeee" followed by the target "eeeE"). A similar task was used by Pugh (Pugh et al., 1996; Pugh et al., 1997). Target stimuli were presented once in the RVF and once in the LVF.

2.2. Procedure

Words were presented on a 40 cm monitor. The participants sat at a distance of 80 cm from the computer screen, with their head in a chin rest. The inner edge of the target was at a distance of 1.6 cm from the digit of central fixation. This corresponds approximately to a visual angle of 1.1°. The maximum angle sustained by the outer edge was 1.4°.

Each trial was composed of a stimulus (the standard) presented in the center of the screen for 1500 ms, followed by an asterisk which appeared in the center of the screen for 1000 ms. After this, two simultaneous events occurred: a digit (6, 4, or 2) appeared centrally, and the target was presented on its left or right, randomly, for 175 ms. The participant had 3000 ms to respond to the target with a key press and to report the digit orally. The interstimulus interval lasted for 3000 ms. These timing characteristics were established in advance, on the basis of pilot studies on a small group of deaf and hearing

Table 1
Pairing of lateral stimuli for rhyme and semantic tasks

	Mean length	Mean class of frequency	Mean subjective frequency	Mean letters shared with central stimulus
Rhyme task				
Yes RVF	4	390	3.7	2
Yes LVF	4	376	3.4	2
No RVF	4	363	3	2
No LVF	4	360	3.1	2
Semantic task				
Yes RVF	4.2	377	3.5	
Yes LVF	4.2	347	3.2	
No RVF	4.2	370	3.4	
No LVF	4.2	377	3.1	

children. In the rhyme task, the participant had to decide whether the two stimuli were rhyming or not. In the semantic task, he or she had to decide whether the two words belonged to the same semantic category. Finally, in the visual task, he or she had to decide whether or not the two stimuli were visually identical. The participant had to press the response key in the direction of the computer for "yes" responses, and in his or her own direction for "no" responses. The correct repetition of the digit ensured that the participant effectively fixated the center of the screen. The order of the key response to the target and the repetition of the digit was not constrained by the paradigm. A control experiment, in which subjects were told to respond first to the target word and then to the digit confirmed that this situation did not affect the results (see Appendix B). These stimuli sequences were displayed by the MEL program (Schneider, 1988). A training block of 24 items preceded each experimental task. This training block could be repeated if necessary. Each experimental task consisted of two blocks of equal numbers of items, separated by a short break.

The order of the three tasks was counterbalanced across participants. In addition, two versions of the rhyme and semantic tasks were constructed. The words that appeared in the right visual field in the first version were presented in the left visual field in the second version, and vice versa. Half of the subjects were shown the first version, and the other half were shown the second version.

After the participant completed the experiment on the computer, his or her reading abilities were measured by a cloze reading test, the Lobrot test (Lobrot, 1973), where he or she had to choose the correct word to complete the cloze, and by a paper-and-pencil time-constrained lexical decision task of 100 items, with a maximum duration of 90 s. The participant was also asked once again to give his judgement on the experimental material of the rhyme and of the semantic conditions, but this time in a paper-and-pencil test. The experiment lasted 1 h and 30 min, or two sessions of 45 min, depending on the time available for the subjects.

2.3. Participants

All participants were right-handed. In a laterally questionnaire, they reported using the right hand for least 11 of 15 everyday life activities. They reported having either no vision problem or having corrected vision.

2.3.1. Hearing participants

All hearing participants were native French speakers. The group of hearing adults was composed of university students who reported no history of hearing impairment. They were either paid or received course credit for their participation.

A group of hearing children was also recruited. They received a reward for their participation in the experiment. All of the children attended a regular state elementary school. Table 2 (upper section) displays the characteristics of the hearing participants.

2.3.2. Deaf participants and their hearing controls

Youngsters who were congenitally and profoundly deaf were recruited. The hearing loss of each deaf participant was quantified using the oldest audiogram available. The mean hearing loss in the better ear of the deaf group was 104 dB HL (range: 90–125 dB), averaged over the frequencies 500–1000–2000 Hz. Twelve participants wore hearing aids, and two had a cochlear implant. Ten of the participants were mainstreamed in schools for hearing youngsters with the help of a CS interpreter, while the other four attended a school for the deaf which used CS-based communication. All deaf participants had hearing parents. For eight of the deaf participants, CS had been used regularly at home and at school since the mean age of 15 months, and for the other six, CS had only been used at school and in a speech therapy context since the mean age of 59 months. It appeared from the analyses of results that the home CS users and the school CS users performed at a similar level in the control and the experimental tasks. Therefore, the results will be reported for the whole group of CS users.

Fourteen hearing participants were selected from among the groups of adults and children described

Table 2
Description of hearing and deaf participants

	N[a]	Mean age in years[b]	Lobrot[b] (number of sentences correctly processed in one minute)	Lexical decision[b] (number of items correctly processed in one minute)	Semantic judgement (max: 80)[b]	Rhyme judgement (max: 80)[b]
Hearing adults	32 (13)	20 (18–24)	12 (18–24)	71 (37–98)	79 (77–80)	79 (61–80)
Hearing children	18 (9)	11 (10–13)	7 (4–12)	38 (22–51)	76 (62–80)	74 (51–80)
Deaf CS users	14 (6)	16 (10–23)	8 (3–12)	45 (33–57)	76 (62–80)	70 (57–80)
Hearing controls	14 (7)	14 (11–20)	8 (4–12)	45 (22–73)	76 (62–80)	75 (51–80)

[a] Number of males in brackets.
[b] Range in brackets.

above. Each hearing participant was matched as closely as possible to a deaf participant with regard to age, sex, reading level, and performance on the paper-and-pencil tests (see Table 2).

3. Results

3.1. Experimental tasks

Mean percentages of correct responses were calculated for "yes" and "no" responses in the two visual hemifields, for the three tasks. Mean reaction times (RT) for correct responses were also computed but are not reported here. Indeed, RT analyses were mostly non-informative (i.e., showing no significant effect) or redundant with analysis of accuracy (i.e., RT effects were mostly going in the same direction). Items for which the digit was not correctly reported were excluded from statistical analysis of accuracy. These represented 2.3% of the data for the rhyme task, 2.5% for the semantic task and 1.9% for the visual task.

The data were first analysed in two overall ANOVAs with repeated measures on Tasks (Semantic, Rhyme, and Visual), Laterality (RVF and LVF), and Response (yes and no). In the first analysis, hearing children were compared to hearing adults. In the second analysis, the deaf participants were compared to their hearing controls.

The first analysis yielded a significant effect of Laterality, $F(1,48) = 27.24$; $p < .001$, and a significant interaction between Laterality and Task, $F(2,96) = 11.21$; $p < .001$. The second analysis yielded a significant Laterality effect, $F(1,26) = 12.08$; $p < .005$, and significant interactions between Group and Laterality, $F(1,26) = 5.16$; $p < .05$, and Task and Laterality, $F(2,52) = 3.35$; $p < .05$. Because of the significant interactions appearing in the two analyses, we decided to pursue the analysis of each task separately.

For each of the three tasks, two $2 \times 2 \times 2$ analyses of variance were conducted on accuracy, with Laterality (RVF and LVF) and Response (yes and no) as the within subjects factor, and Group as the between subjects factor. In the first analysis, hearing children were compared to hearing adults, In the second analysis, the deaf participants were compared to their hearing controls.

3.1.1. Semantic task

Table 3 shows the mean percentage of correct responses for "yes" and "no" responses, for each visual hemifield, and for the hearing children and adults (upper section) and the deaf CS users and their hearing controls (lower section). Ninety-five percent confidence intervals have been computed around each of these means. All these intervals excluded the 50% value, corresponding to chance level, but one ("yes" responses in LVF in hearing children).

Table 3
Mean percent correct responses (standard deviation in brackets) for hearing children and adults (upper section) and deaf CS users and hearing controls (lower section) in the semantic task

	Yes		No	
	RVF	LVF	RVF	LVF
Hearing adults	87 (10)	74 (14)	87 (13)	82 (13)
Hearing children	67 (14)	54 (15)	66 (23)	63 (21)
Deaf CS users	75 (22)	70 (17)	82 (12)	74 (17)
Hearing controls	72 (11)	60 (10)	71 (20)	66 (22)

The analysis comparing hearing children and hearing adults yielded significant main effects of Group, $F(1,48) = 53.11$; $p < .001$, and of Laterally, $F(1,48) = 27.44$; $p < .001$. Hearing adults performed better than hearing children (*M*: 83 and 62%, respectively), and performance was higher when targets were presented in the right visual field (*M*: 77%) than when presented in the left visual field (*M*: 68%). The main effect of response was nonsignificant, $F(1,48) = 1.99$. There was a significant Laterality by Response interaction, $F(1,48) = 11.63$; $p < .001$. Planned comparisons showed that a significant Laterality effect occurred for "yes" responses, $F(1,48) = 34.71$; $p < .001$ ($M = 80\%$ RVF and 67% LVF), as well as for "no" responses, $F(1,48) = 4.43$; $p < .05$ ($M = 80\%$ RVF and 75% LVF). No other interactions were significant.

Correlations were computed between the difference in percentage of correct responses in the right versus the left visual hemifield for "yes" and "no" responses considered together (Laterality effect), and the various control measures (Lobrot reading score, performance on the paper-and-pencil semantic task, age of the participants). None of these correlations were significant.

To sum up, hearing children achieved a lower accuracy rate than adults. Better performances were obtained for targets presented in the right visual field than for those presented in the left visual field. This LH advantage was constant across age groups, and was present for "yes" responses, and, to a lower extent, also for "no" responses.

The analysis comparing deaf CS users and their hearing controls revealed a main effect of Laterality, $F(1,26) = 18.99$; $p < .001$, the RVF giving rise to more correct responses than the LVF (75 and 68%, respectively). There was no effect of Response, $F(1,26) = 1.62$; $p > .05$, and no effect of Group, $F(1,26) = 2.57$; $p > .05$. No interaction was significant. There was no significant correlation between the Laterality effect and any of the control variables (Lobrot reading score, age, performance on the paper-and-pencil task). In summary, the data of the deaf participants were indistinguishable from that of their hearing controls; the LH advantage was similar in both groups.

3.1.2. Rhyme task

Table 4 shows the mean accuracy for "yes" (i.e., rhyming) and "no" (i.e., non-rhyming) responses for each visual hemifield, and for the hearing children and adults (upper section) and the deaf CS users and their hearing controls (lower section). Ninety-five percent confidence intervals have been computed around each of these means. All these intervals excluded the 50% value, corresponding to chance level, but two ("yes" responses in LVF in hearing controls and in deaf CS-users).

The analysis comparing hearing children and hearing adults yielded significant main effects of Group, $F(1,48) = 36.36$; $p < .001$, of Response, $F(1,48) = 13.43$; $p < .001$, and of Laterality, $F(1,48) = 30.18$; $p < .001$. The Group by Response interaction was also significant, $F(1,48) = 5.97$, $p < .05$: children's performance was similar for rhyming (M: 64%) and non-rhyming responses (M: 67.5%), while adults' performance was lower for rhyming (M: 78%) than for non-rhyming (M: 93%) responses. The Laterality by Response interaction was also significant, $F(1,48) = 30.53$; $p < .001$. Planned comparisons showed a better performance for targets presented in the right visual field than in the left visual field occurred for rhyming responses, $F(1,48) = 52.12$; $p < .001$ ($M = 79\%$ RVF and 63% LVF), but not for non-rhyming responses, $F(1,48) < 1$ ($M = 80.5\%$ RVF and 80% LVF). There was no Laterality by Group, nor Laterality by Response by Group interactions.

In order to achieve a better understanding of the abilities associated with the Laterality effect, correlations have been computed between the Lobrot reading score, the performance on the rhyme paper-and-pencil task, subjects' age, and the difference between percentage of correct responses in the right versus the left visual hemifield for rhyming responses (the Laterality effect). The correlation between Laterality effect and performance on the paper-and-pencil control task was marginally significant, $r(49) = .24$, $p = .058$. When age was controlled for, this correlation remained approximately the same, $r = .25$, $p < .09$.

In summary, subjects were more accurate with non-rhyming than with rhyming words. The LH advantage was present for rhyming responses, but not for non-rhyming responses. Hearing children performed similarly for rhyming and non-rhyming pairs, while adults performed better for non-rhyming than for rhyming pairs. Finally, better performance on the control paper-and-pencil test tended to be correlated with greater Laterality effect on the experimental task.

The analysis comparing deaf participants and their hearing controls revealed main effects of Laterality, $F(1,26) = 7.45$; $p < .05$, and of Response, $F(1,26) = 7.69$; $p < .05$. There was no main effect of Group, $F(1,26) < 1$. There was a significant Laterality by Group interaction, $F(1,26) = 7.80$; $p < .05$, demonstrating that the Laterality effect was not the same for the two groups. Further analyses indicated that hearing participants showed significantly more correct responses in the RVF compared to the LVF, $F(1,13) = 14.78$; $p < .01$, while deaf participants did not, $F(1,13) < 1$. The Response by Group interaction was not significant, $F(1,26) < 1$. The Laterality by Response interaction was significant, $F(1,26) = 29.15$; $p < .001$, while the Laterality by Response by Group interaction was not, $F(1,26) = 2.52$; $p = .12$. Planned comparisons showed that there was a significant main effect of Laterality, $F(1,26) = 17.89$; $p < .001$ for rhyming responses, and no Laterality effect, $F(1,26) < 1$ for non-rhyming responses. The correlations between the Laterality effect on rhyming responses and the performance at the paper-and-pencil rhyming task was not significant, $r(28) = .30$; $p > .10$.

To sum up, both groups of deaf and hearing participants showed better accuracy for non-rhyming than for rhyming responses. While hearing controls showed an LH advantage for rhyming responses, deaf participants did not. Note that the absence of Laterality effect in the deaf students cannot be ascribed to a floor-effect. Indeed, the performance of the deaf CS-users was above chance level in all conditions, but one ("yes" responses in LVF) and this was also the case for their hearing controls who showed the Laterality effect.

3.1.3. Visual task

Table 5 shows the mean percentage of correct responses for "yes" and "no" responses, for each visual hemifield, and for the hearing adults and children (upper section) and the deaf CS users and their hearing controls (lower section). Ninety-five percent confidence intervals

Table 4
Mean percent correct responses (standard deviation in brackets) for hearing children and adults (upper section) and deaf CS users and hearing controls (lower section) in the rhyme task

	Yes		No	
	RVF	LVF	RVF	LVF
Hearing adults	87 (12)	69 (17)	92 (8)	94 (6)
Hearing children	71 (21)	57 (18)	69 (21)	66 (23)
Deaf CS users	65 (19)	58 (22)	69 (25)	76 (19)
Hearing controls	74 (19)	49 (16)	74 (20)	74 (24)

Table 5
Mean percent correct responses (standard deviation in brackets) for hearing children and adults (upper section) and deaf CS users and hearing controls (lower section) in the visual task

	Yes		No	
	RVF	LVF	RVF	LVF
Hearing adults	78 (15)	83 (14)	83 (12)	80 (11)
Hearing children	64 (21)	65 (13)	60 (24)	55 (20)
Deaf CS users	69 (16)	73 (17)	71 (18)	69 (17)
Hearing controls	72 (19)	73 (16)	70 (25)	66 (22)

have been computed around each of these means. All these intervals excluded the 50% value, corresponding to chance leve1, but two ("no" responses in RVF and LVF in hearing children).

The ANOVA on the data of hearing adults and hearing children revealed a significant main effect of Group, $F(1,48) = 37.67$; $p < .001$: adults responded more accurately than children (*M*: 81% versus 61%, respectively). The main effects of Laterality and Responses were not significant. None of the interactions were significant. There was no significant correlation between the Laterality effect and any of the control measures (Lobrot reading score and age).

To sum up, there is an absence of any VF advantage in the visual task. The absence of Laterality effect could not be due to floor effect, because the performance was above chance level in all conditions for all groups, except for "no" responses by hearing children.

The ANOVA on the data of the deaf CS users and their hearing controls revealed no effect of Laterality, $F(1,26) < 1$, no effect of Response, $F(1,26) < 1$, and no effect of Group, $F(1,26) < 1$. No significant Laterality by Group interaction, $F(1,26) < 1$, Response by Group interaction, $F(1,26) < 1$, Laterality by Response interaction, $F(1,26) = 1.70$; $p > .05$, or Laterality by Response by Group interaction was observed, $F(1,26) < 1$. No significant correlations were obtained between the measure of Laterality effect and any of the control variables.

3.1.4. Comparison of the rhyming and the semantic conditions

If the RVF advantage indicates that the left hemisphere is better at linguistic processing, one could expect to detect a relationship between the Laterality effect observed in the semantic task and that observed in the rhyme task. For hearing adults and children considered together, this correlation narrowly reached significance level, $r(49) = .28$; $p < .05$. This indicates that the larger the Laterality effect in the rhyme condition, the larger the Laterality effect in the semantic condition. However, there was a large dispersion. On matched groups of deaf CS-users and hearing subjects, the correlation was almost nil, $r(28) = .02$. The same correlation was computed separately for the two sub-groups. For the hearing controls, the correlation, although not significant, was in the expected direction: $r(14) = 0.49$; $p = .08$. However for the deaf CS users, the correlation was in the opposite direction, $r(14) = -.41$, although not significant ($p = .14$).

To sum up, while hearing subjects showed the expected relationships between the Laterality effects observed in the semantic and the phonological tasks, the deaf participants did not. In this latter group, the Laterality effect observed in the semantic task does not seem to be linked from that observed in the rhyme task.

3.1.5. Control tasks

A summary of results on control tasks is presented in Table 2. Among hearing adults and children, all measures were highly correlated with age (all p's $< .005$). The partial correlation analysis, after controlling for the effects of age, showed the following significant correlations between control tasks : Lobrot with rhyme paper-and-pencil ($r = .38$; $p < .01$), and with semantic paper-and-pencil ($r = .33$; $p < .05$); lexical decision with rhyme paper-and-pencil ($r = .36$; $p < .05$); Lobrot with lexical decision ($r = .65$; $p < .0001$). All differences between hearing adults and hearing children were significant (all p's $< .05$ at least).

Table 2 also shows the results on control tasks of deaf participants and their hearing controls. The two groups did not differ in age, Lobrot test, lexical decision, rhyme and semantic paper-and-pencil control tasks (all p's $> .15$ at least). Significant Pearson correlations were obtained between the Lobrot reading test and performance on the paper-and-pencil semantic task ($r = .39$; $p < .05$) between the Lobrot test and age, $r = .39$; $p < .05$, and between the Lobrot test and the lexical decision test, $r = .67$; $p < .001$. When age was partialled out, only the correlation between the Lobrot test and the lexical decision test remained significant, $r = .65$; $p < .001$.

4. Discussion

The present study was designed to investigate hemispheric specialization for semantic and phonological processing of written words in a sample of deaf, proficient readers who were exposed to CS, and in hearing controls, selected from larger groups of hearing children and adults. In a visual hemifield paradigm, three tasks were used: a rhyme task, a semantic task, and a visual task. For the rhyme and semantic tasks, an RVF advantage, interpreted as a left hemispheric superiority, was expected for hearing participants. For the visual task, no left hemispheric superiority was expected. The main question was whether this pattern of results would also emerge for the deaf group. We will begin by discussing the effects observed on hearing participants, including the interaction between Laterality effect and Response that appeared in the two linguistic tasks. We will then discuss the similarities between deaf and hearing subjects observed in the semantic task, and the differences in the rhyming task. Finally, we will suggest possible directions for future research.

Before that, it seems necessary to discuss the fact that accuracy levels are sometimes close to chance levels, and whether this may explain the absence of Laterality effects in some conditions. From the confidence interval analysis, it appeared that the conditions where the performance could not be distinguished from chance level were those in which a "yes" response was required to a target appearing in the LVF in the linguistic tasks (hearing children in the semantic task, deaf CS-users and hearing controls in the rhyme task) and a "no" response to targets in both hemifields in the non-linguistic task (hearing children in the visual task). It seems thus safe to suggest that the difficulty to process and answer positively to targets in the LVF was *specific* to linguistic processing, and not general across all conditions (because it did not appear in the visual task). Moreover, the absence of Laterality effects did not seem to be related to "floor effects," because hearing controls did show a Laterality effect in the rhyme task, while deaf CS-users did not, while both groups performed at chance level on the "yes" responses in the LVF. Our Laterality effects (or absence of Laterality effect) could thus be interpreted with a reasonable amount of degree of confidence.

The first major result from this study is the observation of an RVF advantage in hearing individuals in the semantic and rhyme tasks, while no consistent Laterality effect appeared in the visual task. The RVF advantage in the two tasks requiring linguistic processing is consistent with an interpretation in terms of left hemispheric superiority. Indeed, the absence of Laterality effect in the visual task demonstrates that neither the fact that the stimuli were letters, nor the necessity to retain the first sequence in order to make the yes/no decision, were sufficient to explain the Laterality effect in the semantic and in the rhyme tasks. It also renders the scanning habit interpretation of the Laterality effect improbable. Indeed, if the scanning habit was at the root of the Laterality effect observed in the rhyme semantic tasks, an RVF advantage would also have appeared in the visual task. This was not the case (see Jordan et al., 2000 for a more detailed discussion on this point).

Besides the global RVF advantage, the semantic and the rhyme tasks differed in some aspects. First, an interaction between the Laterality effect and Response occurred in both tasks; however, the Laterality effect was significant both for "yes" and "no" responses in the semantic task, but only on "yes" responses in the rhyme task (see Rayman & Zaidel, 1991 for similar results in a rhyme task). Second, the accuracy rate was similar for "yes" and "no" responses in the semantic task, while a larger amount of correct responses for "yes" than for "no" decision appeared in the rhyme task (see Grossi et al., 2001; Rayman & Zaidel, 1991 for similar results). What explanations could be offered for these differences? As RVF advantage indexes the superiority of the left hemisphere for language processing, the data suggest that the linguistic processing of the semantic information occurred for "yes" as well as for "no" responses in the semantic task. One needs to access the lexical representation to decide that two words belong to the same category as well as to decide that two words do not belong to the same category. In that situation, the left hemisphere is involved, with the same accuracy, in the "yes" decision as in the "no" decision. In the case of the rhyme task, access to the phonological representations of words is needed in order to decide that the two words rhyme. Indeed, a comparison of the vowel *and* the following consonant is needed for the "yes" response. A more superficial level of processing could perhaps be used in order to decide that two words do not rhyme, because detecting one difference (in the vowel or in the following consonant) is sufficient. Subjects could also reject pairs as non rhymes by detecting orthographic differences at the end of the words. The present data thus suggest that the right hemisphere is able to judge that two words are not rhyming as efficiently as the left hemisphere, while it is less efficient with regard to the analytical process required for judging that two words are rhyming.

For both the semantic and the rhyme task, the Laterality effect was stable across the age/reading level groups included in this study, suggesting that the neural systems involved in semantic processing as well as in the matching of phonological information for written words have already reached a mature organization by the age of 11 (see Grossi et al., 2001 for similar data on a rhyme task).

The second major result from this study concerns the comparison between deaf participants and hearing controls matched as closely as possible with the deaf on age, sex, and linguistic skills. In the semantic condition, results from deaf and hearing participants were indistinguishable. To our knowledge, few, if any, studies have found comparable Laterality effect for age-matched deaf and hearing controls, and this is the first evidence of left hemisphere specialization for semantic processing of written language in deaf people exposed to CS. The present results suggest that similar cerebral systems were employed by hearing and deaf participants in semantic processing, which is minimally affected by the modality (visual vs. auditory) of early linguistic experience. They parallel Neville et al.'s (1992) data showing similar cortical electric activity in response to content written words in hearing subjects and in deaf people who are native signers. They are also compatible with Neville's claim that the acquisition of competence in the grammar of language is determinant in establishing the specialization of the left hemisphere for language.

In the rhyme task, an interaction between Laterality effect and Groups was observed. While hearing controls displayed an RVF advantage for the 'yes' responses, deaf participants did not. The absence of left hemisphere superiority in deaf CS users is striking for two reasons. First, these subjects achieved a high level of rhyming, as attested by their high performance on the paper-and-pencil control task in the present study, as well as by previous reports of good rhyming abilities in deaf CS users (Charlier & Leybaert, 2000; La Sasso et al., in press). Second, studies performed in normally hearing subjects using PET (Démonet et al., 1992, 1994) or fMRI (Fiez, 1997) have shown that phonological tasks induce strongly lateralised responses within the predominant hemisphere, within the cortical regions located around the Sylvian fissure, while the semantic component of word semantic judgment tasks is known to induce more bilateralised responses.

It is possible that the rhyme task recruited neural resources differently in hearing and in deaf students. In hearing subjects, reading words is an ability grafted upon an acquired spoken language. Word reading elicit an activation of the primary auditory cortex, a region involved in the most basic aspects of auditory processing (Haist et al., 2001). The brain regions most commonly activated in functional imaging studies of normal readers using various rhyming tasks are left-hemisphere inferior frontal cortex (BA 44 and 45, Broca's motor areas), the left inferior temporal gyrus (BA 37), and the left supramarginal gyrus (BA 40) (Price, 1997). For deaf CS users, word reading is grafted upon an acquired visual language, made of lip movements and hand cues. From other studies conducted in our laboratory, we know that the perception of linguistic stimuli delivered in CS is left-lateralised, particularly in participants who were exposed to CS early and intensively (Leybaert & Alegria, 2003; Leybaert & D'Hondt, 2003). But we don't know yet which brain areas are activated during the perception of CS, nor during the processing of written words by CS users. While hearing children can use additional (auditory) information to determine whether two visually presented stimuli rhyme, CS users may also use additional information, related to the cues they have attached to these lexical items, when learning these words (see Leybaert & Lechat, 2001a). Given the difference between deaf and hearing students in the sensory information that gives rise to phonology, it is possible that the task of rhyme judgment elicit *less* activation of the left hemisphere auditory cortex in deaf students than in hearing ones. There is some data from connected research suggesting that the areas activated during speech-reading perception are not as left-lateralized in deaf people as they are in hearing people. MacSweeney et al. (2001) found that a group of congenitally deaf whose first language was spoken English showed significantly less *left* temporal activation than a group of hearing, when performing a simple speech-reading number task. They concluded that "hearing speech helps to develop the coherent adult speech perception system within the lateral areas of the left temporal lobe" (p. 437). It is thus possible that early experience with a visual language rather than an auditory one has an impact on the lateralization in processing sub-lexical units of the language. Imagery studies of the cerebral regions activated in CS users performing rhyming tasks, or more classical phonological loop tasks, and even reading tasks are necessary to test this hypothesis (see Eden, Cappell, La Sasso, & Zeffiro, 2001 for a first attempt).

In conclusion, our data provide evidence of distinct effects of early language experience on the development of brain processes involved in semantic and phonological decisions. The indices of left hemisphere specialization for semantic processing of written words, similar in deaf, proficient readers who have been exposed to CS and in their hearing controls suggest that semantic processes housed in the left hemisphere develop independently of the nature of the early linguistic experience. By contrast, the absence of left hemisphere superiority for rhyme processing in deaf CS users suggests that the neural systems involved in rhyming tasks change their organization as a function of the first linguistic experience. More research, involving brain imagery, is needed to gain a clearer picture of lateralization of different language processes in relation to the nature of language experience.

Acknowledgments

This work has been supported by the Foundation Van Goethem-Brichant, by a mini-ARC grant, and by a ARC grant "La Structure du Lexique Mental" (no. 96-01-203) of the Université Libre de Bruxelles. We want to thank Marie Sandron and Josiane Lechat for their efficient help in the collection of the data, Francis Goossens for the development of appropriate software for analysis and testing. We would like to express special thanks to all the participants, especially deaf participants, and extend our gratitude to their families for the information they gave us, and for their interest in our research. We also want to thank the professionals in Deaf Education for their active and enthusiastic collaboration. Finally, we address our thanks to Daniel Holender who suggested the control experiment, and to Carol LaSasso who helped correct our English.

Appendix A. Material

	Yes responses		No responses	
	Central stimuli	Lateral stimuli	Central stimuli	Lateral stimuli
Rhyme condition	lieue	feu	vieux	vue
	gare	car	lard	dur

Appendix A (*continued*)

	Yes responses		No responses	
	Central stimuli	Lateral stimuli	Central stimuli	Lateral stimuli
	pelle	gel	celle	lac
	bébé	clé	pâté	bas
	paire	mer	chair	riz
	pain	faim	gain	rail
	dent	sang	vent	bond
	chaud	faux	saut	date
	laid	très	paix	jour
	villa	chat	pizza	voir
	poids	bois	soie	défi
	loque	bloc	coq	cour
	doux	sous	roux	rôle
	mari	tapis	gentil	colle
	cahier	payer	noyer	décor
	caisse	pièce	nièce	linge
	place	basse	masse	signe
	cheval	balle	total	raton
	cross	gosse	écosse	peine
	score	sport	port	poste
	nœud	jeu	queue	rue
	tard	bar	part	tir
	belle	sel	ruelle	île
	curé	blé	vider	bec
	terre	fer	hier	cas
	bain	sein	sain	mois
	chant	gens	camp	coin
	peau	haut	beau	dame
	mai	prêt	fait	roue
	bras	papa	plat	vrai
	doigt	fois	froid	dire
	rock	choc	phoque	pile
	tout	coup	goût	tige
	petit	fusil	copie	laver
	copier	loyer	papier	foire
	stress	fesse	laisse	litre
	tasse	glace	trace	crème
	ovale	salle	local	câlin
	féroce	bosse	brosse	botte
	bord	corps	fort	vitre
Semantic condition	jus	thé	eau	cri
	chien	âne	jambe	bus
	menton	nez	loup	pré
	huit	six	sept	âge
	cou	main	frère	sens
	sœur	mère	train	lame
	camion	tram	hockey	cube
	volley	boxe	salade	taxi
	céleri	pois	lilas	pavé
	tulipe	iris	pore	toit
	vache	cerf	bouche	nuit
	rouge	gris	beige	fête
	noir	jaune	vert	ville

Appendix A (*continued*)

	Yes responses		No responses	
	Central stimuli	Lateral stimuli	Central stimuli	Lateral stimuli
	robe	gilet	pull	bâton
	cerise	poire	pêche	balai
	hêtre	sapin	frêne	radio
	banc	chaise	divan	carte
	ciel	orage	neige	barbe
	france	suède	italie	corde
	homme	fille	enfant	coeur
	café	vin	lait	col
	lapin	rat	foie	sol
	joue	dos	lion	bal
	cinq	dix	neuf	roi
	pied	tête	oncle	voix
	tante	père	avion	tube
	bateau	moto	course	noix
	tennis	vélo	tomate	clou
	oignon	chou	pensée	loin
	muguet	rose	veau	cage
	poule	ours	oeil	soir
	mauve	brun	orange	pipe
	bleu	blanc	violet	repas
	jupe	veste	gant	crâne
	banane	melon	pomme	crêpe
	érable	chêne	saule	plage
	bureau	table	lit	route
	soleil	pluie	nuage	piano
	suisse	grèce	chine	danse
	garçon	femme	parent	porte
Visual condition	Eeee	Eeee	Eeee	eeeE
	aAaA	aAaA	aAaA	aAAA
	rrRR	rrRR	rrRR	RRrr
	EEEE	EEEE	EEEE	EEeE
	AaaA	AaaA	AaaA	aAAa
	rRRr	rRRr	rRRr	RrrR
	EEEe	EEEe	EEEe	EeEe
	aaAA	aaAA	aaAA	Aaaa
	RRRR	RRRR	RRRR	rrrR
	EeeE	EeeE	EeeE	eEEe
	Aaaa	Aaaa	Aaaa	aaAa
	RRrR	RRrR	RRrR	RrRr
	eeEE	eeEE	eeEE	Eeee
	AAAa	AAAa	AAAa	AaAa
	Rrrr	Rrrr	Rrrr	rrRr

Appendix B. Replication of the experiment

In order to control the effect of the double response on the digit and on the lateral stimulus, we have replicated the experiment on hearing adults, this time requiring subjects to respond first to the lateral stimulus, and then to the digit.

B.1. Method

B.1.1. Participants

Twenty-two hearing right-handed adults (12 women and 10 men) participated in this experiment. Their mean age was 21 years old (18–25). All reported having no vision problems or had corrected vision. They were paid for their participation.

B.1.2. Material and procedure

The material was the same as that used in the main experiment. The procedure was also similar except that the order of responses was constrained. Each trial was composed of a central stimulus presented in the center of the screen for 1500 ms, after which an asterisk appeared in the center of the screen for 1000 ms. The asterisk was then replaced by a digit (6, 4, or 2), and a word was presented simultaneously on its left or right, randomly, for 175 ms. The participant had 2000 ms, to respond with a key press to the lateral stimulus. Subsequently, a message instructed the participant to repeat the digit. The interstimulus interval was 3000 ms. Participants were encouraged to respond as quickly and as correctly as possible to the lateral stimulus.

B.2. Results and discussion

Mean accuracy was calculated for "yes" and "no" responses in the two visual hemifields, for the three tasks (see Table 6). Items for which the digit was not correctly reported were excluded from statistical analyses. These represented 3% in the semantic task, and 2% in the rhyme and the visual condition. Two by two analysis of variance with repeated measures was conducted on accuracy for the three tasks, with Laterality (RVF and LVF) and Response ("yes" and "no") as within factors.

In the semantic task, a Laterality effect, $F(1,21) = 14.27$; $p < .01$ was observed; the Response effect did not reach statistical significance, $F(1,21) = 3.40$; $p = .08$. There was no Laterality by Response interaction, $F(1,21) = 2.33$; $p > .05$, meaning that the Laterality effect did not differ for "yes" and "no" responses.

In the rhyme task, significant Laterality and Response effects were observed, $F(1,21) = 11.01$; $p < .01$, $F(1,21) = 18.11$; $p < .0001$, respectively. The Laterality by Response interaction was significant, $F(1,21) = 26.21$; $p < .0001$, showing a consistent RVF advantage on "yes" responses and no reliable hemifield difference on "no" responses.

In the visual task, no Laterality effect was observed, $F(1,21) < 1$. There was a significant effect of Response, $F(1,21) = 6.21$; $p < .05$. The Laterality by Response interaction was not significant, $F(1,21) = 2.23$; $p > .05$.

In conclusion, the patterns of Laterality effects on accuracy observed when response to digit is delayed from the response to the lateral stimulus mainly replicate those observed in the main experiment, which can therefore not be attributed to of the response to the digit and to the lateral stimulus being confounded.

Table 6
Mean accuracy (standard deviation in brackets) of hearing subjects on the control experiment for semantic, rhyme, and visual tasks

	Yes		No	
	RVF	LVF	RVF	LVF
Semantic task	88 (7)	79 (12)	90 (9)	86 (9)
Rhyme task	92 (7)	79 (13)	93 (6)	95 (6)
Visual task	87 (7)	90 (8)	83 (12)	81 (14)

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