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Neurolinguistic development in deaf children: the effect of early language experience

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Abstract

Recent investigations have indicated a relationship between the development of cerebral lateralization for processing language and the level of development of linguistic skills in hearing children. The research on cerebral lateralization for language processing in deaf persons is compatible with this view. We have argued that the absence of appropriate input during a critical time window creates a risk for deaf children that the initial bias for left-hemisphere specialization will be distorted or disappear. Two experiments were conducted to test this hypothesis. The results of these investigations showed that children educated early and intensively with cued speech or with sign language display more evidence of left-hemisphere specialization for the processing of their native language than do those who have been exposed later and less intensively to those languages.

Introduction

Despite many studies over the past decades, the question of the impact of deafness on neurological development, and, more particularly, on cerebral dominance for language processing, remains unresolved. Many authors have concluded that deafness interferes with the neural processes responsible for the development of cerebral dominance (Conrad, 1979; Gibson, 1988). The reasons invoked to explain such findings are all based on the notion of an interaction between an innate predisposition and environmental conditions in the development of the neural bases underlying language processing. However, they differ by the critical factor invoked. Some authors have argued that deprivation of auditory experience is responsible for the lack of left-hemisphere specialization (Mykelbust, 1966; McKeever, Hoemann, Florian & VanDeventer, 1976). For others, experience with a visuomanual language, the processing of which involves a large visuo-spatial component characteristic of right-hemisphere function, distorts left-hemisphere specialization (Poizner, Battison & Lane, 1979). Finally, delayed experience with linguistic input constitutes a risk factor for the disappearance of bias for left-hemisphere specialization (Bonvillian, Orlansky & Garland, 1982; Conrad, 1979; Leybaert, 1998; Neville, 1991; Phippard, 1977). Moreover, these various factors are often interrelated in deaf people, making difficult the appreciation of their relative importance in the lateralization of language processing. Therefore, if we want to learn about how the development of cerebral lateralization is influenced by environmental conditions, it is useful to first describe the effects of these conditions among children with normal hearing.

The hearing child

This hearing child is born with a well-developed neurological structure adapted for hearing and later on for speaking. He is born into an environment of sound, including the sounds of speech. The auditory processes, from those of the peripheral hearing mechanism to the neuronal networks of the auditory cortex, continuously transmit and process sensory information. This process continues to shape the underlying structures, and further determines the characteristics that are relevant in the linguistic environment (Jusczyk, 1997). In this developmental process, when do the first signs of cerebral specialization for language appear, and for what aspects of language?

In the newborn, and even in the fetus, the anatomical asymmetries that exist in right-handed adults are already present (i.e. a planum temporale that is larger in the left than in the right hemisphere). Whether these anatomical asymmetries already correspond to functional asymmetries, or whether they represent only the neural substrate of later functional asymmetries, is still under discussion. Some authors have found that 2- and 3-month-old infants show, in a dichotic listening situation, a right-ear advantage for detection of changes in phonemes, and a left-ear advantage for detection of changes in musical notes (Bertoncini et al, 1989). Others have not found such differences (Best, Hoffman & Glanville, 1982). Limitations of the behavioural techniques with young infants may account for these divergent results (Dehaene-Lambertz, Christophe & Van Ooijen, 2000).

Evoked potentials seem to constitute a very promising technique for investigating more directly the development of cerebral specialization in speech perception by infants. Dehaene-

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Lambertz recently found a dominance of the left hemisphere for processing sounds in 4-month-old infants. However, no evidence of greater left-hemisphere involvement in phonetic processing (syllables) than in acoustical processing (tones) was found, suggesting that the left advantage for phonetic processing is not present or is still weak during the first months of life (Dehaene-Lambertz, 2000).

In older babies, aged 13–20 months, Mills, Coffey-Corina & Neville (1993, 1997) have studied the responses to comprehended words, unknown words, and backward words. A negative response, around 200–350 ms after stimulus onset, was found for comprehended and unknown words, but was very weak for backward words. This indicates different processing of sounds based on whether or not they consist of speech stimuli. From 13 to 17 months, the difference in event-related potential (ERP) components between comprehended and unknown words was apparent over anterior and posterior regions of both hemispheres; at 20 months of age, the effects occurred only over regions of the left hemisphere. In order to ascertain the role played by linguistic development, children were divided into two groups, as a function of number of words produced. Distinct responses to comprehended and unknown words were recorded over temporal and parietal regions of the left hemisphere, but only among the children with the more developed language production abilities (Mills et al, 1993, 1997).

The same researchers also compared the patterns of brain activity in response to open-class (nouns, verbs, adjectives) and closed-class (prepositions, adverbs) words. At 20 months (when children were speaking in single-word utterances or beginning to put two words together), open- and closed-class words elicited similar patterns of brain activity. At 28–30 months (when children begin to speak in short phrases), open- and closed-class words elicited different patterns of brain activity. By 3 years of age (when children speak in sentences and used closed-class words to specify grammatical relations), ERPs revealed a left-hemisphere asymmetry with regard to closed-class words. Similar patterns of results are observed in adult subjects. The organization of brain activity seems to be linked to language abilities rather than to chronological age. This was established by comparing children of the same age (20 months) who differed in language abilities. No ERP differences in response to open- and closed-class words were observed in children with small vocabulary size, while in those with large vocabulary size, the ERP differences were similar to the 28–30-month patterns (Neville & Mills, 1997).

To sum up, there are few empirical data in favour of a functional difference between the left and right hemispheres at a very early age. In hearing children, lateralized cerebral function for speech develops during the 3 first years of life. Also, among these children lateralized function seems to be more dependent on linguistic experience than on chronological age per se. The development of left-hemisphere specialization possibly occurs through a shift away from right-hemisphere involvement. Indeed, in the case of abnormal linguistic experience, the right hemisphere seems to be more involved than the left hemisphere in processing language (Locke, 1998).

The deaf child

The child born deaf presents a striking contrast to the hearing child. Among deaf children, there is no evidence that the neurological structures specialized for the development of language are not identical to those of hearing children, except in cases of gross malformation. However, these neurological structures are not fed by the sensory input in the same way. Deaf and hearing children differ in two main respects. The first difference is that the linguistic input is mainly visual for the deaf, instead of auditory. There is now plenty of evidence that the left cerebral hemisphere is specialized for language, regardless of the nature of the language medium. Comprehension and production of sign language (SL) is strongly disturbed in case of left-hemisphere stroke (Corina, 1998; Rönnberg, Söderfeldt & Risberg, 2000). This does not exclude a greater involvement of the right hemisphere in the processing of SL (Neville et al, 1997), the interpretation of which is still under discussion (Bavelier, Corina & Neville, 1998; Hickok, Bellugi & Klima, 1998; Paulesu & Mehler, 1998).

The second difference is that, while hearing children are continuously exposed to a structured linguistic input from birth, deaf children may not have access to a language fully specified at the phonological and grammatical levels, unless visual methods of communication are used. Many children who are born deaf go through the first critical years of life in linguistically deprived situations, even if they are diagnosed and fitted with hearing aids during the first 2 years of their lives. Indeed, lipreading and the use of residual hearing does not allow the child educated orally to obtain full access to the oral language delivered by the parents. At the phonological level, features such as voicing and nasality are invisible (Erber, 1974). Consequently, many lexical items have similar lipread images. Morpho-syntactical morphemes (prepositions, plurals, past tense, etc.) are generally short, uninflected words that are not very visible on the lips (Taeschner, Devescovi & Volterra, 1988). For the deaf child educated orally, there is little possibility that neurological structures will receive the audiovisual stimulation that is so essential for further development. Also, the signed communication used by hearing parents who are not proficient in SL may not constitute a linguistic input sufficiently structured, at the grammatical level, to foster the development of cerebral specialization.

If early experience is abnormal or absent, the initial bias for left-hemisphere specialization for language can vanish or be distorted, because the growth of the expectant neurological structures can cease or be severely retarded. Evidence for the possibility that the left-hemisphere specialization is compromised in cases of abnormal early linguistic experience comes from studies both on deaf adults and on deaf children.

Studies on deaf adults

Neville and co-workers (Neville & Bavelier, 1996, 2001; Neville, 1991; Neville et al, 1997; Neville, Mills & Lawson, 1992) proposed that a left-hemisphere specialization for processing of language is determined by the grammatical competence of the subject in that language. In a hemifield study requiring the identification of written words, they found that, while hearing subjects showed behavioural and electrophysiological left-hemisphere asymmetry, deaf subjects who had acquired American Sign Language (ASL) as first language did not. Most of the deaf participants did not acquire full grammatical competence in English, and this may be the reason why they did not display left-hemisphere specialization during reading. More direct evidence for this conjecture was obtained in a study of ERPs during sentence reading. The closed-class words elicited specific ERPs that were most evident over the left hemisphere, and this indicates grammatical processing. This specific response to closed-class words was absent from ERPs of deaf subjects who scored lower on tests of English grammar, but was present in deaf subjects who scored nearly perfectly on tests of English grammar. Importantly, the responses of the deaf to lexical/semantic processing, elicited by content words, were indistinguishable from those of hearing participants. Thus, these data support the idea that the acquisition of grammatical competence in a language is a necessary condition for the development of left-hemisphere specialization for that language.

Neville and co-workers also investigated whether the involvement of the left hemisphere in processing language occurs independently of the modality of the language first acquired. ERPs recorded in response to open- and closed-class signs in ASL sentences displayed similar characteristics to those observed in studies of English. However, in native signers (both hearing and deaf), the activity elicited by closed-class ASL signs was bilateral and extended to include parietal regions of both left and right hemispheres. These finding suggest that the processing of a language based on spatial contrasts and motion relies on resources localized in right-hemisphere regions. By contrast, hearing people who acquired ASL in their late teens did not show the pattern observed in native signers in response to closed-class signs, while their responses to semantic information were similar to those of native signers. Finally, the same authors performed functional magnetic resonance imaging (fMRI) studies that compared sentence processing in English and ASL. When hearing adults read sentences written in English, their first language, robust activation emerged in the Broca region, specifically within the left hemisphere. When deaf adults read English, their second language, learned late and imperfectly, such an activation within the left hemisphere was not observed. When the same deaf subjects were viewing sentences in their native language, ASL, the same Broca region of the left hemisphere that was active when native speakers of English processed written English sentences, was activated. This indicates that the Broca region is pre-wired to process grammatical languages, independently of the modality and structure of these languages. Importantly, if the language is not acquired within the critical time window, as is the case for deaf people learning English, this predisposition within the left hemisphere may not be expressed.

Studies of deaf children

Studies which have so far been reported have used either the visual hemifield paradigm or the concurrent task technique. In a typical visual hemifield experiment, a subject visually fixates a central point while test items are exposed for a few milliseconds (less than 250 ms, the duration of eye saccade) in either the left or the right half-field, or simultaneously in both half-fields. Familiar words, letters or pictures of manual signs are used as test material. The subject is required to report what he has seen. It is assumed that the visual information upon which identification depends is transmitted only to the specified hemisphere. Identification of linguistic material does not just involve the visual areas of the brain. Information is also processed by areas concerned with language processing. Left cerebral dominance is assessed by reference to whether the subject gives more correct responses to items exposed to the right visual field (left hemisphere) than to the left, and this is compared with results from hearing subjects at the same task.

As it applies to deaf children, a review of the studies based on the visual hemifield paradigm is largely disappointing: some studies showed a left-hemisphere advantage, others a right-hemisphere advantage, and others no hemisphere advantage at all for natural language (i.e. signs of ASL) as well as for written language processing (Conrad, 1979; D'Hondt, 2001; Gibson, 1988). This inconsistency may be largely due to the heterogeneity of language experiences of the participants, which was not controlled for in these earlier studies. To date, no published study has related hemispheric dominance findings in deaf subjects to the age of exposure to a first language.

We assume that early exposure to SL or to cued speech (CS) can provide the conditions for the development of grammatical competence in language, and thus provide an adequate input to those neurological structures which are specific for language processing. SL is not sound-based, but displays each of the characteristics of all formal languages, including a phonology and a complex grammar, and makes extensive use of spatial location and hand motion (Stokoe, Casterline & Cronenberg, 1965). CS is a system that clearly and completely conveys visually the information provided by speech to hearing people (Cornett, 1967). In French, CS is composed of eight hand shapes to convey consonants, and five different placements around the face to code the vowels. Phonemes that are easily distinguishable by speech reading are coded by the same hand shape or the same placement. Conversely, phonemes that have similar lip shapes are coded by different hand shapes and placements. Information given by the code and information given by speech reading are complementary. Previous studies have shown the beneficial effects of CS on speech perception and on the development of linguistic abilities, at the lexical and syntactic levels (Hage, Alegria & Périer, 1991). Children exposed early and intensively to CS develop meta-linguistic abilities such as rhyming (Charlier & Leybaert, 2000; LaSasso, Crain & Leybaert, 2003), reading, and spelling (Leybaert, 2000; Leybaert & Lechat, 2001). The benefit of CS is particularly marked when it has been used early by the parents with their deaf child (early CS users) and less important when introduced later and less intensively in school (late CS users).

We predicted that early CS users and early SL users would display clear evidence of left-hemisphere specialization for the processing of CS and SL respectively. By contrast, late CS users and late SL users, who have impoverished language experience during their first years and who do not have full grammatical competence in their language, may have an atypical development of cerebral dominance for language processing. We tested these hypotheses in two experiments, one involving perception, and the other production, of linguistic stimuli (D'Hondt, 2001).

Perception of linguistic stimuli

In a first experiment, we compared the lateralization patterns of early and late CS users and SL users in a task that involved the perception of dynamic linguistic stimuli. The stimuli were digital videos of one-handed signs in the sign version of the experiment, and monosyllabic consonant–vowel words produced with a single hand shape at a single position in the CS version. These videos were reduced to five images, corresponding to a total duration of 200 ms. In each trial, subjects had to compare a centrally presented video with a video presented only in either the left or right visual hemifield. Eighty pairs of stimuli were constructed, each pair consisting of one central and one lateral video. Two tasks were used on the same videos. The non-linguistic task involved a visual judgment: are the signs (or the cues) of the two videos produced by the same hand independent of the stimulus produced? No linguistic processing was required to perform this task, which could entail a similar performance of both hemispheres. The linguistic task involved the comparison between the two signs (or the two CS words): is the same sign (or CS word) produced on the two videos, independently of the hand used to produce it? For this linguistic task, we expected a right visual field advantage, more among the early SL users and the early CS users than among the late SL users and late CS users. The pairs of stimuli were presented twice to each subject, once incorporated in the linguistic task, and once incorporated in the non-linguistic task. The order of the two tasks was counter-balanced across subjects. Half of the targets were presented to the left visual hemifield, and the other half to the right visual hemifield. Among the 40 targets presented to one hemifield, 20 required a 'yes' response (the target video was the same as the standard), and the other 20 required a 'no' response.

The SL version of the experiment was administered to 49 right-handed subjects. Among these, 12 deaf subjects constituted the early SL group. All had deaf parents, and used Belgian French Sign Language as their primary and preferred mode of communication. The 11 deaf subjects who constituted the late SL group all had hearing parents. They acquired SL at school at different ages (after they were older than at least 6 years) and used SL at school at the time of testing. The control subjects consisted of university students who did not know either SL.

The results were clear-cut. In the linguistic condition, we obtained a significant right visual field advantage in percentage correct response for the early SL group, and, unexpectedly, for the control hearing group as well. No visual field advantage was observed among the late SL group. In the non-linguistic condition, no visual field advantage was observed, in either group (Table 1).

The CS version of the experiment was administered to 43 right-handed subjects. The early CS group was composed of 12 deaf subjects whose parents used CS to communicate with them at home, from a mean age of 22 months. The late CS group was composed of 14 congenitally deaf persons exposed to CS from a mean age of 61 months. All deaf CS users had hearing parents. Seventeen (17) French-speaking university students with normal hearing participated in the experiment as control subjects.

Again, the results were clear. As expected, for the linguistic task, we obtained a right visual field advantage only for the early CS group. The late CS group, and the hearing control subjects, did not have a right visual field advantage. In the non-linguistic task, no visual field advantage was observed among any of the three groups of subjects (Table 2).

The present results indicate that the superiority of the left hemisphere is manifest for visual languages. Thus, left-hemisphere involvement is not specific to auditory or written languages. These results contribute to the already existing evidence that the left cerebral hemisphere is specialized for language, regardless of the nature of the language medium. Also, the data suggest that the neural systems that mediate the processing of linguistic information can be modified in response to language experience. The left-hemisphere superiority for language processing appears more systematically in children exposed early to a grammatical linguistic input (SL or CS) than in children exposed late to this input. One puzzling aspect of the results is the left-hemisphere advantage obtained by hearing people when perceiving signs (without any sound) in the linguistic condition. The reason for this effect remains unclear. Hearing people may tend to interpret some of the signs linguistically, either because some of them were iconic, or because they were told that the stimuli were signs of the SL used by the deaf, or because they tended to recode the stimuli verbally. Further experiments are needed to explain this latter finding.

Production of linguistic stimuli

Another paradigm that has been used to infer hemisphere specialization for language processing is the concurrent activities paradigm (Kinsbourne & Cook, 1971). Subjects are required to do two very simple tasks simultaneously: to tap with their left or right index finger as fast as possible on a telegraphic key, and to repeat linguistic or non-linguistic stimuli. In the baseline condition, the rate of tapping (with the left or the right hand) is measured. In the experimental conditions, the rate of tapping is measured when the subject is simultaneously performing a concurrent (linguistic or non-linguistic) task. The relative degree of disruption of the left/right tapping provoked by the concurrent task is taken as an index of the cerebral lateralization of the

Table 1. Perception of signs experiment: percentage correct responses (standard deviation in parentheses) as a function of condition (linguistic, non-linguistic), visual hemifield, and group of subjects

	Linguistic condition		*Non-linguistic condition*	
	LVH	*RVH*	*LVH*	*RVH*
Hearing	87 (8)	91 (5)	94 (5)	93 (4)
Early signers	90 (9)	93 (8)	87 (9)	87 (11)
Late signers	94 (4)	93 (4)	79 (14)	78 (19)

LVH, left visual hemifield; RVH, right visual hemifield.

Table 2. Perception of cued speech experiment: percentage correct responses (standard deviations in parentheses) as a function of condition (linguistic, non-linguistic), visual hemifield, and group of subjects

	Linguistic condition		*Non-linguistic condition*	
	LVH	*RVH*	*LVH*	*RVH*
Hearing	80 (6)	81 (10)	96 (4)	94 (7)
Early CS users	78 (13)	83 (13)	86 (20)	85 (17)
Late CS users	87 (5)	88 (8)	90 (11)	92 (8)

LVH, left visual hemifield; RVH, right visual hemifield.

processing induced by the concurrent task. If the two activities are controlled by the same hemisphere, there will be intra-hemispheric resource competition, which will cause more interference with the tapping than if the two activities are controlled by different hemispheres. For example, tapping with the right hand and producing language are both controlled by the left hemisphere, while tapping with the left hand and producing language are controlled by different hemispheres. A larger degree of disruption of the right-hand tapping than of the left-hand tapping by concurrent language production would indicate that language is controlled by the left hemisphere. By contrast, in the case of no hemispheric specialization for language, the same degree of disruption of the left-hand and of the right-hand tapping should be observed. Finally, the production of non-linguistic gestures (such as grimaces or arbitrary gestures) should entail the same amount of disruption of the left- and the right-hand tapping.

Thus far, studies reported with deaf subjects have addressed two different questions. Is there a critical period for the activation of left-hemisphere dominance for speech production? Is the left hemisphere specialized for linguistic processing, in signed as well as in spoken speech? Marcotte & Morere (1990) completed a series of studies in which deaf and hearing adolescents between the ages of 13 and 20 years were required to tap while simultaneously repeating aloud the verbal stimuli 'ba-ba-ba', 'cat-dog-horse', or 'how are you'? They found that subjects with normal hearing, and subjects with deafness acquired after 3 years of age, showed the typical larger disruption of the concurrent verbal production task on the right tapping than on the left tapping, which indicates a left-hemisphere dominance for speech production. Congenitally deaf subjects and children with early acquired deafness (between the ages of 6 and 36 months) displayed atypical cerebral representation: one-third showed left-hemisphere dominance, one-third right-hemisphere dominance, and one-third a bilateral representation. The authors concluded that linguistic/auditory exposure and experience up to the age of 3 years is critical in the activation of left-hemisphere dominance for speech production (Marcotte & Morere, 1990). It may also be the case that it is early exposure to a structured linguistic input that is critical for language production, regardless of the sensory modality of the language medium (auditory or visual). Deaf children who are raised in a signed environment are deprived auditorily during the early years, but they need not be linguistically deprived to the same degree as equally deaf children dependent on spoken language input. The study of the pattern of disruption in this population is important for the contribution it could make to answering the question of whether the dominance of the left hemisphere for language production extends to non-phonetic languages: in other words, whether the dominance reflects a speech function or a language function.

The study of Corina, Vaid & Bellugi (1992) provides relevant information about this question. The investigators examined the relative pattern of tapping disruption on the right and the left hand under concurrent conditions of shadowing speech, shadowing sign language, shadowing arbitrary motoric gesture, and shadowing symbolic gesture (in these latter three conditions, people tapped with one hand and shadowed with the other hand). In one experiment, involving hearing people born to deaf parents, it was found that the shadowing of SL provoked more disruption of the tapping rate than the shadowing of speech; however, both speech and sign produced significantly greater right-hand than left-hand tapping disruption. This indicates that, despite differences attributable to language modality, the left hemisphere is involved in production for both signed and spoken language. In another experiment, the same authors examined whether there is a dissociation in lateralization pattern for linguistic stimuli (i.e. signs) and non-linguistic movements (symbolic gestures, such as waving goodbye, and arbitrary gestures, such as non-meaningful sequences of limb movement) in congenitally deaf, native signers, born to deaf parents. Only shadowing of SL resulted in significantly greater right-hand interference. No significant asymmetries were found for the shadowing of either arbitrary or symbolic gestures. These results support the notion that SL production is subserved by the left hemisphere in native signers (Corina, Vaid & Bellugi, 1992).

We predicted that the pattern of lateralization for signed or spoken language production could be affected by the precocity of language experience. We investigated whether greater left-hemisphere involvement in language production is observed in children who are exposed to a grammatical language (SL or CS) very early than in children for whom a structured grammatical environment is made available only when they enter school.

In the audiovisual experiment, hearing subjects had to shadow audiovisual French words and grimaces presented on videotape. In the signed experiment, the deaf subjects' task was to shadow (i.e. repeat) a list of common one-handed signs of Belgian French Sign Language and grimaces presented on videotape. In the CS experiment, deaf CS users had to shadow a list of common CS words and grimaces presented on videotape. While shadowing these stimuli, subjects had to concurrently tap, as quickly as possible, a telegraph key, which recorded the number of taps in 30 s. Subjects completed each condition while tapping with the left and with the right hand. Baseline tapping rates for each hand were collected before and after the concurrent task lists, and were averaged. A percentage decrement score was computed for each hand, in each condition: (baseline – concurrent task)/baseline $\times$ 100.

The results showed good patterns of differences between groups (Tables 3, 4 and 5). In hearing subjects, there was a significant interaction between condition and laterality: as expected, only shadowing of audiovisual speech resulted in significantly greater right-hand interference than left-hand interference. No significant asymmetries were found for the shadowing of grimaces (Table 3). In both groups of deaf CS users, the interaction between condition and laterality was not significant. However, the results of the early CS group were more similar to those of the hearing group; specifically, a greater right-hand than left-hand tapping disruption was observed when shadowing CS stimuli. This pattern was not observed in the late CS group (Table 4). In the SL experiment, a marginally significant interaction between hand effect and condition was obtained in the early signers. For sign shadowing, a larger disruption was observed on the right hand than on the left hand. No significant asymmetry was found for grimace shadowing. In the late SL group, no difference was observed between left-hand and right-hand tapping disruption when shadowing signs (Table 5).

First, our results indicate that there was greater overall left-hemisphere involvement in the production of both spoken and signed languages. The left-hemisphere specialization appears

Table 3. Tapping experiment: mean percentage decrement (standard deviations in parentheses) between the numbers of tappings in the baseline condition and in the shadowing condition as a function of laterality and conditions: hearing subjects

	Audiovisual condition		*Grimace condition*	
	Left hand	*Right hand*	*Left hand*	*Right hand*
Hearing adults	4 (5)	7 (4)	14 (8)	14 (9)
Hearing children	3 (7)	8 (6)	14 (10)	14 (8)

Table 4. Tapping experiment: mean percentage decrement (standard deviations in parentheses) between the numbers of tappings in the baseline condition and in the shadowing condition as a function of laterality and conditions: CS subjects

	Cued speech condition		*Grimace condition*	
	Left hand	*Right hand*	*Left hand*	*Right hand*
Early CS users	4 (8)	8 (6)	13 (9)	14 (7)
Late CS users	11 (10)	11 (11)	16 (13)	14 (12)

Table 5. Tapping experiment: mean percentage decrement (standard deviations in parentheses) between the numbers of tappings in the baseline condition and in the shadowing condition as a function of laterality and conditions: signing subjects

	Signing condition		*Grimace condition*	
	Left hand	*Right hand*	*Left hand*	*Right hand*
Early SL users	15 (8)	18 (10)	14 (7)	13 (10)
Late SL users	18 (6)	16 (6)	14 (5)	12 (5)

for shadowing linguistic movements but not for shadowing non-linguistic movements, even if these are expressed within the same (oral or manual) modality. Second, the data suggest that the neural systems that mediate language production can be modified as a function of language experience. When shadowing a language, a large and more systematic disruption occurred for the right-hand tapping than for the left-hand tapping condition among children exposed early to grammatically structured input (signed or cued) than in children exposed only later to this input.

General conclusions and perspectives

The studies described here provide the first evidence that the age of exposure to a structured linguistic input determines the pattern of cerebral organization for language in deaf children. In the absence of appropriate input during a critical time window, there seems to be a risk that the initial bias for left-hemisphere specialization will disappear or be distorted. As previously stated, we did not expect all deaf people exposed late to a structured language to show abnormal dominance for verbal material, and this did not happen. However, what was expected, and generally what happened, was a pattern of dominance different from that of subjects exposed early to a structured linguistic input. There are two important uncertainties here. First, we do not know the exact relationship between structure and environment. It is possible that structural and functional growth continues normally until a threshold deficit of linguistic input is reached, at which point growth is totally inhibited. Or it is possible that a close relationship exists between organic and functional development on the one hand, and sensory deficit on the other. Second, we do not know whether interindividual variability plays an important role in this development. We only want to argue that there is a risk that the absence of appropriate linguistic input associated with deafness can permanently disrupt neurological organization.

As such, our data constitute an empirical basis for early language stimulation by parents and speech therapists. This stimulation may constitute a precipitating factor in cerebral lateralization for language perception and production. The development of normal left-hemisphere specialization may be at the root of acquisition of linguistic abilities, as well as of metalinguistic abilities. Therefore, the investigation of the development of left-hemisphere specialization of deaf children fitted with cochlear implants should be one of the priorities of investigators interested in knowing how cerebral lateralization interacts with early exposure to a structured linguistic input. Would there be a maturational delay in the development of left-hemisphere specialization in implanted children that approximates the period of auditory deprivation prior to implantation?

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