uids[10] will profit from the results obtained in the present simulation. □

José Teixeira is in the Laboratoire Léon Brillouin (CNRS/CEA), CE Saclay, 91191 Gif-sur-Yvette, France.
e-mail: teix@llb.saclay.cea.fr

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Neuroscience

Right on in sign language

Eraldo Paulesu and Jacques Mehler

Language is a unique faculty of the human mind[1], and even the congenitally deaf can acquire it in the form of sign language[2]. For more than a century — ever since the pioneering research of Paul Broca and Carl Wernicke, who first identified some of the key areas concerned — we have known that spoken language is represented in the brain's left hemisphere. But much remains mysterious about this lateralization of function. Is the left hemisphere concerned with language as a side-effect of the ability to process language-specific acoustic stimuli, or has grammar simply emerged there? Are all natural languages processed and represented in this part of the brain? Are all of the languages spoken by a polyglot processed by the same neural net? And are the same cortical areas used for the sign languages of the congenitally deaf and for the oral languages of the hearing?

A new study by Neville *et al.*, published last month in *Proceedings of the National Academy of Sciences*[3], raises some provocative issues about the cerebral organization of language in both deaf and hearing subjects. Neville and colleagues used functional magnetic resonance, a brain-imaging technique that can reveal the areas activated when subjects accomplish a task such as understanding sentences. They studied cerebral activity while subjects were processing sentences either in American Sign Language (ASL) or in written English.

Three groups of people were studied: (1) hearing monolingual speakers of English; (2) 'native' deaf signers (now properly called speakers) of ASL; and (3) hearing bilingual speakers of ASL and English. Subjects in group 3 were born to deaf parents and were exposed to sign language from birth; most had deaf siblings. The mastery of ASL in groups 2 and 3 was similar. Likewise, English proficiency was comparable in groups 1 and 3. The English proficiency of the deaf subjects in group 2 is said to have been only moderate; nevertheless, the three groups understood the English sentences presented during the experiment equally well.

During the scanning session, subjects watched two kinds of visual stimuli: first, videos of a deaf native ASL speaker producing sentences in ASL and, second, English sentences presented on a screen one word at a time. To identify the areas concerned with ASL processing or with reading English sentences, the activation due to the nonlinguistic properties of the stimuli was subtracted using two baseline tasks — looking at meaningless hand movements and meaningless strings of consonants.

As expected, the hearing volunteers with no knowledge of ASL showed no increase in brain activation when looking at ASL tapes. Moreover, Neville *et al.* observed an increase in activation in the left hemisphere when deaf or hearing subjects processed their native language (Fig. 1). These activated areas were located around the Sylvian fissure: that is, the inferior frontal gyrus (Broca's area), the superior temporal gyrus (including Wernicke's area) and also the left prefrontal cortex. More surprisingly, when processing sign language, native speakers of ASL (deaf and hearing) displayed a comparable increase of activation in equivalent areas of the right hemisphere. Finally, the deaf subjects showed a bilateral increase in activity while reading.

With the exception of the bilateral representation of sign language in native speakers of ASL, these findings are compatible with other observations involving hearing subjects[4–6]. But although right-hemisphere activation associated with processing of oral and written language has been reported before[4–6], it was not as pronounced as activation of the left hemisphere. As far as we are aware, Neville and colleagues' report of almost symmetrical hemispheric language

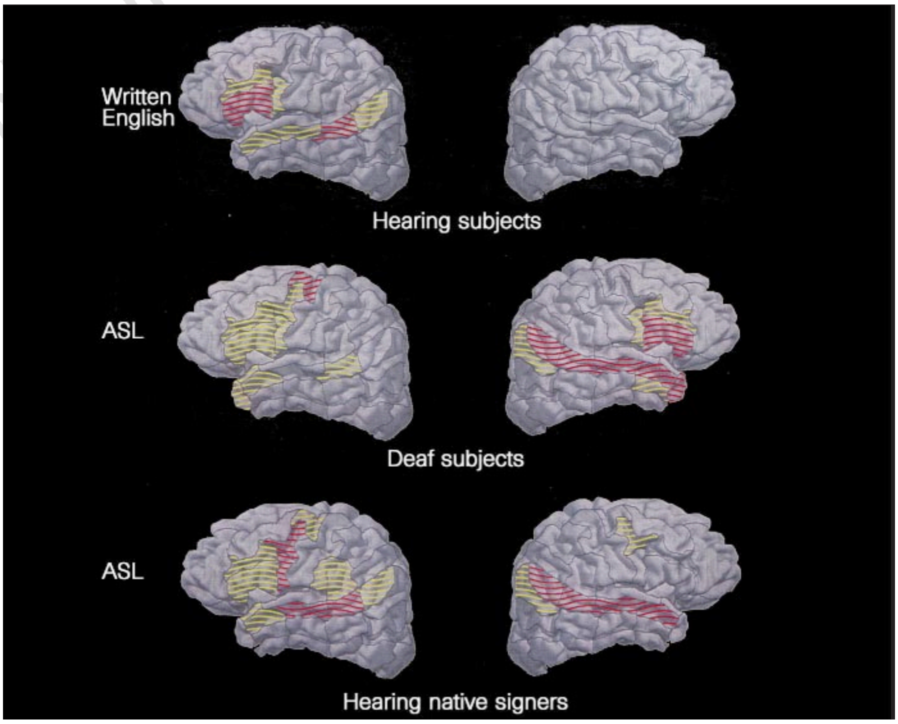

Figure 1 **Summary of the findings of Neville *et al.*[3] in imaging the areas of the brain activated when various subjects processed American Sign Language (ASL) or written English. The top row shows the areas activated when hearing monolingual speakers of English processed written English. The left hemisphere is much more active than the right. A similar pattern of activation was observed when a group of hearing native speakers (signers) of ASL processed written English. In comparison, a group of deaf ASL speakers showed less activation in the left hemisphere and also some activation in the right hemisphere (not shown). The second and third rows show the activation when sentences were processed in ASL: in both groups of native speakers of ASL, a bilateral pattern of activation was evident. As expected, the brain of monolingual non-ASL-speakers was not activated by ASL. Statistical significance of regional activation: red indicates $P<0.0005$; yellow, $P<0.005$; grey no activation. (Reproduced from Figs 1 and 2 of ref. 3.)**

representation for sign language in hearing or deaf native speakers of ASL is unprecedented, and it is the most challenging aspect of their data.

For instance, the finding runs counter to observations with brain-damaged native speakers of ASL, in which injury to the left hemisphere (but not the right) often impairs their ability to use and understand ASL (aphasia)[7]. Given that Neville and colleagues' results imply that, in native ASL speakers, much of their right hemisphere is also activated by ASL, why have neuropsychologists failed to observe aphasia in such subjects when their right hemisphere has been damaged? This is an important question, but the uncertainty over the answer is nothing new — other results from imaging and from clinical neuropsychology have yielded partly inconsistent views about the anatomical foundations of language.

However, in this case there are some clues. For instance, Neville *et al.* show that the involvement of the right hemisphere is similar in deaf and hearing native speakers processing ASL sentences. So it seems that the involvement of the right hemisphere in processing ASL cannot result from a remapping of cortical areas because of deafness. Moreover, because the left hemisphere is dominant for oral languages, it is thought that it is the grammar of these languages that is mediated by the left hemisphere.

Could it be that the grammar for sign languages lies elsewhere? ASL uses hand and face movements, so one could imagine that the production and possibly the understanding of sign language require the representation of both sides of the body in the brain, resulting in bilateral activation. This suggestion conflicts, however, with the data of McGuire and colleagues[8], who reported activation of the left prefrontal cortex and Broca's area in deaf speakers of sign language while they were covertly generating sentences in British sign language. They also described a similar pattern of activity when hearing subjects were silently generating English sentences[9].

In explaining the discrepancy between the results of Neville and colleagues' functional imaging and findings from brain-damaged people, one cannot exclude the possibility that the right-hemisphere activation observed for ASL is due to a task-related variable that behaves differently for ASL and English. For instance, written English lacks features present in ASL and spoken languages, such as prosody (that is, rhythm and intonation). Deficits of prosody are seen following lesions to the right hemisphere[10], and so reliance on this hemisphere may be different when reading English words and seeing ASL sentences.

Finally, the investigations of Neville *et al.* also raise questions about the representation of language not only in those people who are bilingual for oral English and ASL, but also for other kinds of bilinguals. Among the authors' subjects were hearing users of ASL who were also highly proficient in English, whereas deaf users of ASL were only moderately proficient in English. The cortical activity of the deaf subjects for English sentences, especially in the left hemisphere, was less marked than in hearing ASL speakers. Age of language acquisition, degree of language proficiency and deafness are correlated in this comparison, so we cannot know which one is responsible for the different representations of English in the two groups of native ASL speakers.

Other investigations of the cortical representation of oral language in bilinguals suggest that proficiency in the second language is important in determining the overlap in the representation of the first and second languages[11,12]. In people who have mastered two oral languages, there are only minute discrepancies between the cortical representations of the languages[13]. By contrast, the hearing native speakers of ASL and of English displayed considerable differences in the cortical representations of the two languages, even though their mastery of the languages was comparable to that of the best bilinguals in oral languages.

Could it be that ASL is implemented in such a unique sensory modality that its cortical representation is also unique, regardless of whether another language shares resources with it? To tackle this question, it might be necessary to explore further the behaviour of brain-damaged ASL speakers or momentarily to block the functioning of parts of the brain in order to understand exactly what their contribution is. A method such as trans-cranial magnetic stimulation[14], which impedes the function of specified cortical areas, may be a useful tool to take this research further. □

Eraldo Paulesu is at the Scientific Institute H. San Raffaele, INB-CNR, Universita' di Milano, via Olgettina 60, 20132 Milan, Italy.
e-mail: epaulesu@mednuc.hsr.it
Jacques Mehler is at the Laboratoire de Sciences Cognitives et Psycholinguistique, CNRS et EHESS, 54 Boulevard Raspail, 75006 Paris, France.
e-mail: mehler@lscp.ehess.fr

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Daedalus

Free captive fish

The fishing industry is approaching a crisis. Once-rich fishing grounds such as the Grand Banks off Newfoundland are denuded; important species such as cod are becoming endangered; national fishing fleets argue ever more bitterly about fishing rights. And yet the obvious answer, fish farming, has problems of its own. For water is poor in food and oxygen, so fish do best in high dilution. Yet a commercial farm must pack its fish as densely as possible: depleting the water of oxygen, polluting it with waste and faecal matter, and maybe spreading disease. Daedalus now has a middle way.

Many fish farms 'wall off' a region of natural water with a net, and breed the fish behind it. Daedalus is taking this idea to extremes. His plan is to raise a shoal of fish to young adulthood in a farm, and then release them within a large net in the open ocean. He is designing a floating circular boom, suspended from which a huge closed net encloses a volume of sea like a vast tea-strainer. The mesh size is chosen so that the fish within the net cannot escape, and their predators (which must be bigger) cannot get at them; neither are they likely to be seriously invaded by unwanted species. At the same time, their food or prey (which must be smaller) can freely enter, and excreta can freely drift out. And, of course, clean bulk sea water will swirl through the net as if it were not there.

The final step is to set the whole thing adrift in the open sea. The fish will not even realize that they are trapped; they will behave like a free-living shoal. But radar reflectors and transponders on the circular boom will tell the owners where it is at any moment. When the fish have had time to grow big enough, a boat can go out to harvest them — either hauling in the net, or towing the whole thing back to port.

An unpowered 'fish corral' will drift freely with the current, and will not sustain a healthy flow of water through it — unless the fish themselves propel it, as they may. If not, its radar reflectors may have to be formed as sails, to drive it through the water. Remote control of those sails could even steer it about, though this erodes the simplicity of the scheme. Many details remain to be worked out; the optimum size of the fish corrals, the best locations for them, and ways of avoiding collisions with ships or hijacking by pirates. But when perfected, Daedalus's fish corrals should avert oceanic ecological disaster while providing a sustainable, predictable supply of healthy and nutritious fish.

David Jones