Neural correlates for the acquisition of natural language syntax

Marco Tettamanti[1], Hatem Alkadhi[2], Andrea Moro[3], Daniela Perani[3,4], Spyros Kollias[2] and Dorothea Weniger[2]

[1] San Raffaele Scientific Institute, Milano, Italy.

[2] University of Zurich, Switzerland.

[3] Vita-Salute San Raffaele University, Milano, Italy.

[4] Institute of Neuroscience and Bioimaging CNR, Milano, Italy.

Address for Correspondence:

Marco Tettamanti, San Raffaele Scientific Institute, Via Olgettina 58, I-20132 Milano, Italy, Tel + +39-02-26434888, Fax ++39-02-26434892; Email: tettamanti.marco@hsr.it

Abstract

Some types of simple and logically possible syntactic rule never occur in human language grammars, leading to a distinction between grammatical and non-grammatical syntactic rules. The comparison of the neuroanatomical correlates underlying the acquisition of grammatical and non-grammatical rules can provide relevant evidence on the neural processes dedicated to language acquisition in a given developmental stage. Until present no direct evidence on the neural mechanisms subserving language acquisition at any developmental stage has been supplied. We used fMRI in investigating the acquisition of grammatical and non-grammatical rules in the specified sense in 14 healthy adults. Grammatical rules compared to non-grammatical rules specifically activated a left hemispheric network including Broca's area, as shown by direct comparisons between the two rule types. The selective role of Broca's area was further confirmed by time by condition interactions and by proficiency effects, in that higher proficiency in grammatical rule usage, but not in usage of non-grammatical rules, led to higher levels of activation in this area. These findings provide evidence for the neural mechanisms underlying language acquisition in adults.

Introduction

The two major determinants of language acquisition are the characteristics of the linguistic input, such as the structural properties of phrases and the distribution of each linguistic item, and the learner's encounter with such an input (Kuhl, 2000; Saffran et al., 1996). The latter involves primarily the degree of exposure to a language and the age of acquisition. Information on the developmental time course of language acquisition in infancy has been gained from normal and neurologically or developmentally impaired children (Fletcher and MacWhinney, 1995). Clinical studies, together with neuroimaging investigations on bi- and multilinguals, have contributed to the identification of the neuroanatomical correlates of language production and comprehension in languages acquired before and after puberty (Abutalebi et al., 2001). However, no direct evidence concerning the neural mechanisms subserving language acquisition at any developmental stage has been forwarded. An unresolved issue pertains to how the brain regions involved in the acquisition of a second language in adulthood are related to the regions involved in processing the mother language.

In adults, specific patterns of neural activity associated with the different language components as defined by linguistic theories have been found. In particular, there is now converging evidence as to the brain areas subserving syntactic processing in the mother language. Many non-fluent aphasic patients with a lesion in left inferior frontal cortical areas (BA 44 and 45) display the clinical syndrome of agrammatism. Agrammatism is characterized by the omission of bound and free-standing grammatical morphemes (Kean, 1985). Furthermore, some agrammatic patients are unable to understand the meaning of a sentence, when functional arguments such as subject and direct object have to be identified on the basis of syntactic structure (Grodzinsky, 2000). In agreement with such clinical findings, neuroimaging studies have revealed activations within and around Broca's area, when healthy adult subjects were required to perform tasks calling for

syntactic processing. Some studies varied the level of syntactic complexity (Caplan et al., 1998; Stromswold et al., 1996), resulting in differential demands on verbal working memory resources. Other studies used materials consisting either of syntactically anomalous sentences (Embick et al., 2000; Meyer et al., 2000; Ni et al., 2000) or of sentence pairs with different syntactic structure, which could be same or different in meaning (Dapretto and Bookheimer, 1999). A drawback of the latter studies is that processing of the pertinent syntactic features is tied up with sentential semantic processing.

To eliminate such confounding semantic effects, Moro and colleagues (Moro et al., 2001) also used a syntactic violation detection task but adopted an innovative experimental approach to study syntactic processing. Syntax was isolated from lexical-semantics (i.e. that portion of semantics that has no role in syntax) by replacing lexical word-roots by phonologically legal pseudowords. In this study, syntactic processing was associated with activation in the circular sulcus, a deep component of Broca's area, in the right inferior frontal gyrus, in the left insula and the left caudate nucleus.

A further issue to be considered in studying the mechanisms of language acquisition is that variations among natural grammars are not totally unbound but rather governed by a highly interconnected net of universal principles (Chomsky, 1981; Seiler, 2000). Some syntactic rule formats, albeit simple and logically possible, have never been found in human languages (Dryer, 1992; Greenberg, 1963). For example, in human languages there are no syntactic rules that are based on the number of words occurring in a given sentence or on mirror-reversals of the linear order of all words in a sentence. Accordingly, a rule such as "the auxiliary verb must immediately follow the third word of the sentence", even if it refers to perfectly identifiable lexical items, is to be considered as "non-grammatical", since it has never been found in any human language grammar. Any syntactic relation in any human language must be established on hierarchical syntactic notions such as subject, predicate, etc., rather than on precedence or subsequence of words in a sentence (Chomsky, 1995). The fact that hierarchical structures must be linearized into sequences of words is

due to the physical constraints of human linguistic communication and has far reaching consequences on the overall design of grammar and the typology of phrase structure (Kayne, 1994; Moro, 2000).

Given that language rules follow a specific set of principles, what happens if the brain is confronted with a non-grammatical rule to learn? Functional magnetic resonance imaging (fMRI) was used to investigate the neuroanatomical mechanisms involved in the acquisition of novel syntactic rules in adults, comparing the effects elicited by syntactic rules of a grammatical (G) and of a non-grammatical (NG) type. We hypothesised that the acquisition of G-rules would engage to a significantly greater extent than NG-rules brain regions known to participate in syntactic processing in the mother language.

The G-syntactic rules were based on functional relationships among the elements of a sentence, such as subject, predicate, etc. (again, defined in terms of hierarchical phrase structure). The NG-syntactic rules, instead, made use of sequential cues specifying the absolute position of some element within the linear sequence of words. The syntactic manipulations originating the novel G- and NG-rules always amounted to position exchanges of words on a string, whether or not they conformed to the human language grammatical universals. Both the acquisition and usage of these two types of novel rules were studied. During the stage of acquisition a syntactic rule had to be extracted. During the stage of usage it was a matter of detecting syntactic violations of acquired rules.

Following the experimental approach adopted in our previous work (Moro et al., 2001), we eliminated lexical-semantics and manipulated the positional level of syntax (Levelt, 1989), selectively. The sole piece of information that had to be acquired consisted of the particular novel syntactic rule introduced, as phonological and the non-manipulated grammatical features were all kept invariant from the volunteers' mother tongue.

Materials and methods

Subjects

14 right-handed volunteer subjects (7 females and 7 males; mean age 27,2 years, range 21-35 years) with a comparable level of education participated in the study. They all were monolingual Italian-speakers from birth, with Italian-speaking parents. None of the subjects had a history of neurological or psychiatric disorders. After receiving an explanation of the procedures, participants gave written informed consent. Right-handedness was verified using the Edinburgh Inventory (Oldfield, 1971).

Experimental design

Four experimental conditions were designed by combining 2 types of syntactic rule (grammatical (G) vs. non-grammatical (NG)) and 2 types of task (rule acquisition (RA) vs. rule usage (RU)). Two baseline conditions controlled for RA and RU tasks, respectively. The experiment thus comprised the following conditions: (a) RA-baseline: reading sentences following mother language syntax; (b) G-RA: reading sentences following a new syntactic rule of a G nature; (c) NG-RA: reading sentences following a new syntactic rule of a NG nature; (d) RU-baseline: detecting violations of mother language syntax; (e) G-RU: detecting rule violations using the G-rule knowledge acquired in (b); (f) NG-RU detecting rule violations using the NG-rule knowledge acquired in (c).

Characteristic sentences for the 6 conditions in the experiment are given below:

a. Rule acquisition baseline (RA-baseline):

"Molte tille bilbavano il daffio."

$(\mathrm{Dem}_{fem/plur} \ \mathrm{N}_{fem/\ plur} \ \mathrm{V\text{-}T/AGR}_{past/3rd\ plur} \ \mathrm{Art}_{masc/sing} \ \mathrm{N}_{masc/sing})$

b. Grammatical rule acquisition (G-RA):

"Molte tille bilbavano daffio il."

(Dem$_{fem/ plur}$ N$_{fem/ plur}$ V-T/AGR$_{past/3rd plur}$ N$_{masc/sing}$ Art$_{masc/sing}$)

Syntactic rule of a grammatical type: The article immediately follows the noun it refers to.

c. Non-grammatical rule acquisition (NG-RA):

"Molte tille il bilbavano daffio."

(Dem$_{fem/ plur}$ N$_{fem/ plur}$ Art$_{masc/sing}$ V-T/AGR$_{past/3rd plur}$ N$_{masc/sing}$)

Syntactic rule of a non-grammatical type : Articles immediately follow the second word in the

sentence.

d. Rule usage baseline (RU-baseline):

Sentences following either mother language syntax as in (a) or containing mother language

syntactic violations as in:

"Tille molte bilbavano il daffio."

(N$_{fem/ plur}$ Dem$_{fem/plur}$ V-T/AGR$_{past/3rd plur}$ Art$_{masc/sing}$ N$_{masc/sing}$)

syntactic violation = wrong word order: N-Dem-V-Art-N instead of Dem-N-V-Art-N.

e. Grammatical rule usage (G-RU):

sentences following either the new grammatical rule as in (b) or containing rule violations as in:

"Molte il tille bilbavano daffio."

(Dem$_{fem/plur}$ Art$_{masc/sing}$ N$_{fem/ plur}$ V-T/AGR$_{past/3rd plur}$ N$_{masc/sing}$)

rule violation = wrong word order: Dem-Art-N-V-N instead of Dem-N-V-N-Art.

f. Non-grammatical rule usage (NG-RU):

sentences following either the new non-grammatical rule as in (c) or containing rule violations

as in:

"Il molte tille bilbavano daffio."

(Art$_{masc/sing}$ Dem$_{fem/plur}$ N$_{fem/ plur}$ V-T/AGR$_{past/3rd plur}$ N$_{masc/sing}$)

rule violation = wrong word order: Art-Dem-N-V-N instead of Dem-N-Art-V-N.

Glosses: Art$_{(gender/number)}$ = article; Dem$_{(gender/number)}$ = demonstrative or quantifying adjective; N$_{(gender/number)}$ = noun; V-T/AGR$_{(tense/agreement)}$ = verb with agreement and tense inflections.

For each type of syntactic structure (G vs. NG) 2 new rules were introduced. G-rule 1: The article must immediately follow the noun it refers to. G-rule 2: The auxiliary verb must immediately follow the main verb it refers to. NG-rule 1: Articles must immediately follow the second word in the sentence. NG-rule 2: The auxiliary verb must immediately follow the third word in the sentence.

In all sentences open-class word-roots were replaced by pseudowords, so as to eliminate lexical-semantic processing (see Moro et al., 2001). Italian phonology (as encoded in graphic form), inflections, function words and grammatical rules (with the exception of the novel syntactic rules introduced) were maintained.

Silent reading was required for all conditions. Subjects were asked to perform the following tasks: in conditions a, b and c to press a response button immediately after having read each sentence. In conditions b and c only, they were additionally told that all sentences followed a new syntactic rule that had to be learned. In d, e and f subjects were required to press the button only if the sentence was correct according to the syntactic structures of a, b and c, respectively. Rules were never made explicit to the subjects before or during scanning sequences. Reaction times and accuracy scores were recorded.

Note that the full variety of Italian articles and auxiliary verbs was used; also note the occurrence of other function words with the same word-lenghth as articles and auxiliaries. This excluded that purely perceptual strategies could have lead to succesful rule inference: the linguistic status of the different words forming a sentence had to be indentified in order to infer the syntactic regularities.

Four scanning sequences were formed, 2 of which introducing a novel G-rule and 2 introducing a novel NG-rule. Sequences consisted of two parts. The one part (experimental) comprised 4 successive alternations between RA and RU experimental conditions (tasks b/e or c/f),

the other (baseline) 4 alternations between baseline conditions (a/d). Each alternation formed a block. Within a block there were two sets of 8 sentences each corresponding to one of the two conditions, thus resulting in a total of 512 sentences (4 sequences x 8 blocks x 16 sentences). Example for a scanning sequence is: $(RA\text{-baseline})_{b1}$-$(RU\text{-baseline})_{b1}$-$(RA\text{-baseline})_{b2}$-$(RU\text{-baseline})_{b2}$-$(RA\text{-baseline})_{b3}$-$(RU\text{-baseline})_{b3}$-$(RA\text{-baseline})_{b4}$-$(RU\text{-baseline})_{b4}$-$(G\text{-}RA)_{b1}$-$(G\text{-}RU)_{b1}$-$(G\text{-}RA)_{b2}$-$(G\text{-}RU)_{b2}$-$(G\text{-}RA)_{b3}$-$(G\text{-}RU)_{b3}$-$(G\text{-}RA)_{b4}$-$(G\text{-}RU)_{b4}$ (b1-b4 subscripts indicate the 4 blocks in each of the two parts forming a sequence). Each subject underwent all 4 scanning sequences. The order of the two parts (experimental and baseline) within a sequence was balanced over the presentation of the four sequences; the four sequences themselves were also presented in a balanced order across subjects. Sentences were balanced for both average number of syllables and average number of words across conditions, sequences and blocks. A fixed presentation time of 3750 ms was used with no interstimulus interval. Full sentences were displayed on a single line and centered in the subjects' visual field.

To familiarize subjects with the task, a trial sequence for each of the two types of syntactic structure (G vs. NG) was administered before positioning subjects in the magnet; different syntactic rules were used than in the experimental conditions.

Data acquisition

Data were acquired on a 1.5 T whole body scanner (Signa Horizon, Echo-speed LX General Electric Medical Systems, Milwaukee, WI) equipped with a standard product transmit-receive head coil. Functional whole-brain imaging was conducted using a T2*-weighted gradient-echo, echo-planar pulse sequence with a repetition time of 2900 ms, an echo time of 58 ms and a flip angle of 85°. Thirty contiguous, axial slices were acquired with a field-of-view of 28x28 cm^2, a slice

thickness of 4 mm and an imaging matrix of 64 by 64 data points, yielding an in-plane resolution of 4.38 mm x 4.38 mm. Series of 205 sequential volumes were acquired for each scanning sequence.

Data analysis

Repeated measures ANOVA was used to test for behavioral effects between conditions (baseline, G and NG) and condition by block interactions. The data of the 4 scanning sequences were pooled together for each individual condition.

Functional MRI data processing and statistical analysis were performed with SPM99 (www.fil.ion.ucl.ac.uk). The entire volume set of each subject was realigned to the first volume of the first sequence. The obtained brain images were then normalized to the Montreal Neurological Institute standard space (closely approximating the space described by the atlas of Tailairach and Tornoux (Talairach and Tournoux, 1988)) to allow for group analysis: transformation parameters were calculated on a structural spin-echo brain image matched to the fMRI images (TE = 12 ms, TR = 700 ms). Prior to statistical analysis, all images were smoothed using an isotropic Gaussian kernel (full width and half maximum = 8 mm) (Ashburner and Friston, 1999). High-pass filtering was used to remove artefactual contribution to BOLD signal. Global differences in fMRI signal were compensated using proportional scaling. Data were then fitted at every voxel using a linear combination of the effects of interest calculated on least-square values. Effects of interest included the timing of condition presentation (box-car) convolved with the SPM99 standard hemodynamic response function. Comparisons between conditions were then made using t-Student statistics. The set of T values given by each voxel of the image produced the statistical parametric map (Friston et al., 1995).

The comparisons between the rule acquisition conditions and the baseline and the direct comparisons between rule acquisition conditions were performed as fixed effect analysis. All the reported activations for these comparisons survived a corrected significance threshold of P<0.05,

except for the G-rule vs. NG-rule acquisition comparison where a small volume correction (SVC, sphere of radius 20 mm) was performed (Worsley et al., 1996), centering on the coordinates of BA 44, 6 and 39 identified in the comparison with the baseline. For control, SVC centering on the same locations was performed also in the NG-rule vs. G-rule acquisition comparison.

Time-parametric statistics were performed by convolving the fMRI time series with a linear regressor, which allows the detection of increases and decreases of activation in time. Time-parametric statistics were performed using a random effect analysis (Frisson and Pocock, 1992). Contrasts between the G-rule and the NG-rule acquisition conditions were calculated by one-sample t-tests (n=14) and masked by the corresponding acquisition condition vs. baseline effects (significance threshold for masking was $P<0.05$ uncorrected). All the reported activations for these comparisons survived an uncorrected significance threshold of $P<0.01$.

For the analysis of the effects of proficiency, with separate procedures for the G-rule and the NG-rule usage conditions, individual accuracy measures were used to divide the experimental data into a "high proficiency" group, which included the subjects with the highest accuracy scores, and a "low proficiency" group, which included the subjects with the lowest accuracy scores (see Table 1). Between group comparisons were calculated by two-sample t-tests using a random effect analysis (Frisson and Pocock, 1992). All the reported activations for these comparisons survived an uncorrected significance threshold of $P<0.001$.

Results and Discussion

Our analysis identified specific neural correlates for the acquisition of G-rules as opposed to NG-rules. We then examined how the activity in such areas is modulated in time and reflected in behavioral measures assessing competence in rule usage.

Rule-type specific neural correlates

Comparisons between the acquisition conditions and their baseline resulted in the identification of the neuroanatomical network participating in the acquisition of G-rules on the one hand and NG-rules on the other. These brain activations are shown in Fig. 1A and Fig. 1B. With both rule types activations in a bilateral fronto-parietal network were found (see Table 2, for the corresponding stereotaxic coordinates). This finding suggests that the activated fronto-parietal network is involved in the acquisition of both hierarchical and non-hierarchical syntactic features. The activation of this network is likely to reflect the participation of multimodal memory systems in learning tasks. Such an interpretation is supported by several neuroimaging studies on learning and memory. Activations in a bilateral fronto-parietal network have been found in an fMRI experiment concerned with learning rules of an artificial grammar (Fletcher et al., 1999), whose syntactic properties differed from those of human language grammars. Similar activation patterns were also obtained in studies concerned with remembering (Marshuetz et al., 2000) or practicing (Wildgruber et al., 1999) verbal items in a particular order. Parietal and frontal regions seem to support separate functions. Some studies have demonstrated that posterior parietal areas, in association with right dorsal premotor areas, subserve visuo-spatial working memory and attention (Jonides et al., 1993; Nobre et al., 1997). Visuo-spatial functions are indeed thought to be required in forming detailed representations of ordered sequences of symbols, such as words forming written sentences. The activations in the middle and inferior frontal gyri appear to reflect operations related to

manipulating and maintaining syntactic information, allowing such information to be synthesized in patterns of regularities. Tasks calling for maintenance and manipulation have indeed been shown to activate prefrontal cortex (Fletcher and Henson, 2001).

Crucially and in agreement with our expectations based on the hierarchical properties of human language grammars, some activation foci were specific for the acquisition of each type of rule: G-rules activated the opercular portion of Broca's area (Brodmann area (BA) 44), the left dorsal premotor area (BA 6) and the left angular gyrus (BA 39). NG-rules activated the right middle frontal gyrus (BA 46) and the right superior parietal lobule (BA 7). These findings indicate that different cortical subcomponents in fronto-parietal regions are activated, depending on whether the rules to be acquired are in line with the universal grammatical properties of human languages or not. In particular, the activation in Broca's area specifically found for the acquisition of grammatical rules is in agreement with the syntactic parsing functions attributed to this brain region (see introduction) and it is well known that lesions in the left premotor area can lead to the syndrome of Broca's aphasia (Mohr, 1978). Thus, the acquisition of novel grammatical rules engages the neural network that sustains the processing of the syntactic aspects of language, specifically.

In order to substantiate these differences further, we performed direct comparisons between the acquisition of novel G- and NG-rules. The left inferior frontal gyrus (BA 44/45, coordinates: x=-44, y=14, z=4, Z score=3.11) and the left ventral premotor area (BA 6, x=-50, y=-4, z=28, Z=3.26) were significantly more activated by G-rules than by NG-rules. Additional activations were found in the left superior temporal and angular gyri (BA 22/39, x=-64, y=-40, z=8, Z=3.99 rsp. x=-34, y=-66, z=20, Z=3.78). NG-rules, in turn, activated the right inferior frontal gyrus (BA 44/45, x=54, y=18, z=16, Z=3.41) and the right superior parietal lobule (BA 7, x=28, y=-52, z=60, Z=5.75). Such findings confirm the specific role of Broca's area and the lateral premotor area in the acquisition of G-syntactic rules. In addition, higher activation of Wernicke's area (BA 22/39) in the

G than in the NG condition is also in agreement with a number of neuroimaging studies investigating syntactic processing (Dapretto and Bookheimer, 1999; Embick et al., 2000; Just et al., 1996).

Temporal changes during the acquisition of novel rules

Our experimental paradigm not only allowed us to measure effects over the entire duration of the acquisition tasks, but also to assess significant temporal changes occurring during rule acquisition. The behavioral data analysis showed that the reaction times in the two acquisition conditions (G-RA and NG-RA) differed significantly from the baseline condition (RA-baseline), both as a main effect and as a condition by block interaction. The interaction effects were analysed by post-hoc paired t-test comparisons between experimental and baseline conditions in the first (block 1) and last (block 4) acquisition blocks: significant differences in block 1 were no longer significant in block 4. Most notably, the results of the ANOVA comparing G-RA and NG-RA were not significant (see Table 3A and Fig. 2A).

While no significant interactions between the acquisition of G-rules and NG-rules were found in terms of behavioral measures, indicating that the acquisition of both rule types was of equal difficulty and took a similar course, the fMRI data analysis revealed significant interaction effects. Time by condition interactions were estimated, revealing brain regions whose activity linearly increased or decreased in time significantly more during the acquisition of G-rules than of NG-rules. These were the opercular portion of Broca' area (BA 44), the left insula, the left superior frontal gyrus (BA 8), the right ventral inferior frontal gyrus (BA 47) and the right inferior parietal lobule (BA 40) (Fig. 2B, C). No brain regions, in turn, were increasingly more activated during the acquisition of NG-rules than of G-rules. These findings give additional support to the hypothesis that Broca's area must be attributed a crucial role in the acquisition of G-rules.

At first this might appear to be counterintuitive, because as rules get more mastered a decrease rather than an increase of activation should be expected in perisylvian areas. Indeed, several studies have shown that automatic language tasks typically do not engage perisylvian cortical areas (Bookheimer et al., 2000; Raichle et al., 1994). Presumably, the monitored time interval of acquisition was too brief to allow for an automatization of grammatical rule processing. Thus, although the novel grammatical rules have been successfully acquired their access still relies on the need to perform detailed syntactic parsing. These findings should be considered along with neuroimaging data on syntactic processing in the mother language. Moro and colleagues (Moro et al., 2001) found activations in a deep component of Broca's area (BA 45), located in the circular sulcus, when examining mother language syntactic processing selectively, while controlling for confounds such as complexity and sentential semantics. Stromswold and colleagues (Stromswold et al., 1996) as well as Caplan and colleagues (Caplan et al., 1998), compared processing of syntactic structures of high and low complexity and found activations on the lateral surface of the opercular portion of Broca's area. It is in this location that linear temporal increases are found in the present experiment. Syntactic complexity and non-automatized rule processing presumably necessitate verbal working memory functions. As has been demonstrated (Paulesu et al., 1993; Zatorre et al., 1992) the opercular portion of Broca's area is indeed associated with verbal working memory. Taken together, such evidence suggests that the acquisition of novel syntactic rules in its less automatized stages depends on a more lateral cortical portion of Broca's area than the one dedicated to syntactic processing in the mother language.

Effects of proficiency in novel rule usage

Most studies on the neuroanatomical correlates of bi- and multilingualism have highlighted on the significance of such variables of linguistic competence as proficiency level, age of acquisition and degree of exposure to a particular language. These studies show comparable levels of activation

in left perisylvian areas elicited by the mother language and the second language in highly proficient bilinguals (Chee et al., 1999; Klein et al., 1995; Perani et al., 1998) and significantly different levels of activation in the same areas in low proficient bilinguals (Dehaene et al., 1997; Kim et al., 1997; Perani et al., 1996). The activation of left perisylvian regions thus seems to be modulated by the level of competence in the second language. This led us to hypothesise that the level at which novel G-rules are mastered would modulate the activation of the brain regions found to participate in the acquisition of those rules.

To test for this hypothesis the effects of accuracy in the usage of the new rules were estimated. Changes in rule usage accuracy level during the course of the experiment were significant for both G-rules and NG-rules, as revealed by the behavioral analysis. Accuracy scores in the two usage conditions (G-RU and NG-RU) differed significantly from the baseline (RU-baseline). This was true both as a main effect and as a condition by block interaction. The interaction effects were analysed by post-hoc paired t-test comparisons between experimental and baseline conditions in the first (block 1) and last (block 4) acquisition blocks: significant differences in block 1 were no longer significant in block 4. Most notably, the results of the ANOVA comparing G-RU and NG-RU were not significant (see Table 3B and Fig. 3A).

In the fMRI data analysis, between group statistics comparing high with low proficient subjects in G-rule and NG-rule usage (see Table 1) were computed. During G-rule usage, the high proficiency group activated Broca's area (BA 44, x=-50, y=16, z=12; Z=3.41) and the left ventral premotor area (BA 6, x=-48, y=-8, z=20; Z=3.82) to a significantly greater extent than the low proficiency group (Fig. 3B). During NG-rule usage, the high vs. low proficiency group comparison revealed a significantly activated focus in the left cerebellar hemisphere (x=-26, y=-68, z=-20; Z=3.49). Thus, competent usage of G-syntactic rules was associated with higher activations in Broca's area and the left ventral premotor area, regions that have been consistently implicated in several aspects of syntactic processing. These findings suggest that, in adulthood, the activity of

specific brain areas within the left perisylvian cortex is modulated by the acquisition of linguistic competence for selected linguistic structures.

Conclusions

Several conclusions can be drawn from the present study. First, this study demonstrates a selective and robust participation of Broca's area in the acquisition of novel G-rules as opposed to NG-rules. Second, the present data help in clarifying the cerebral mechanisms that underlie adult second language acquisition: the gain of competence for novel and selected linguistic features appears to be tightly associated with variations of activity in exactly those perisylvian brain regions implicated in the processing of the corresponding linguistic aspects. Third, in the early stages of language acquisition, the processing of novel linguistic structures engages lateral cortical aspects of Broca's area that support less automatic processes.

All these points elucidate the neural processes participating in the acquisition of grammatical language features in adulthood, as the two types of rules to be acquired only differed from each other at the positional syntactic level; all other variables were held invariant. However, while our data show that a neuroanatomical network comprising Broca's area underlies language acquisition in adults, it is possible that such a network is not specific to language acquisition. G-rules and NG-rules differed to the extent that the former were based on hierarchical syntactic notions, whereas the latter were based on absolute positions within the linear sequence of words. Such a distinction is not unique to language. Visuo-spatial perceptual processing or manual object manipulation can also be either hierarchical or linear (Conway and Christiansen, 2001). Behavioral and neural evidence pointing to an homology between the acquisition of hierarchical strategies for manual object combination and the acquisition of language has been supplied in young children (Greenfield, 1991). Both in their developmental time-course and their neural bases language and manual gestures appear to be tightly correlated (Bates and Dick, in press). Several neuroimaging

experiments in adults show that perception, imitation and spontaneous production of language on the one hand and perception, imitation and spontaneous production of gesture on the other hand activate a partially overlapping distributed network (Bates and Dick, in press). In particular, overlapping activations in Broca's area for language and for gesture execution or observation have been found (Rizzolatti et al., 2001).

To summarize, several pieces of evidence suggest that Broca's area may be a supramodal hierarchical processor. The present study demonstrates that, in adults, the acquisition of linguistic hierarchical syntactic structures depends on a network comprising Broca's area. Our future research will be aimed at showing to what an extent the network including Broca's area overlaps with the neural correlates involved in the acquisition of non-linguistic hierarchical concepts.

References

Abutalebi, J., Cappa, S. F., and Perani, D. 2001. The bilingual brain as revealed by functional neuroimaging. *Bilingualism: Language and Cognition* **4(2)**, 179-190.

Ashburner, J., and Friston, K. J. 1999. Nonlinear spatial normalization using basis functions. *Hum. Brain Mapp.* **7**, 254-266.

Bates, E. and Dick, F. (in press). Language, gesture and the developing brain. In Converging Method Approach to the Study of Developmental Science (B. J. Casey, and Y. Munakata, Eds.), *Developmental Psychobiology* (special issue).

Bookheimer, S. Y., Zeffiro, T. A., Blaxton, T. A., Gaillard, P. W., and Theodore, W. H. 2000. Activation of language cortex with automatic speech tasks. *Neurology* **55**, 1151-1157.

Caplan D., Alpert N., and Waters G. 1998. Effects of syntactic structure and propositional number on patterns of regional cerebral blood flow. *J. Cogn. Neurosci.* **10**, 541-552.

Chee, M. W., Caplan, D., Soon, C. S., Sriram, N., Tan, E. W., Thiel, T., and Weekes, B. 1999. Processing of visually presented sentences in Mandarin and English studied with fMRI. *Neuron* **23**, 127-137.

Chomsky, N. 1981. *Lectures on Government and Binding*. Foris, Dordrecht.

Chomsky, N. 1995. *The Minimalist Program.* MIT Press, Cambridge, MA.

Conway, C. M., and Christiansen, M. H. 2001. Sequential learning in non-human primates. *Trends Cogn. Sci.* **5(12)**, 539-546.

Dapretto M., and Bookheimer S.Y. 1999. Form and Content: Dissociating Syntax and Semantics in Sentence Comprehension. *Neuron* **24**, 427-432.

Dehaene, S., Dupoux, E., Mehler, J., Cohen, L., Paulesu, E., Perani, D., van de Moortele, P. F., Lehericy, S., and Le Bihan, D. 1997. Anatomical variability in the cortical representation of first and second language. *Neuroreport* **8**, 3809-3815.

Dryer, M. 1992. The greenbergian word order correlations. *Language* **68(1)**, 81-138.

Embick, D., Marantz, A., Miyashita, Y., O Neil, W., and Sakai, K. L. 2000. A syntactic specialization for Broca's area. *Proc. Natl. Acad. Sci. USA* **97**, 6150-6154.

Fletcher, P., Buchel, C., Josephs, O., Friston, K., and Dolan, R. 1999. Learning-related neuronal responses in prefrontal cortex studied with functional neuroimaging. *Cereb. Cortex* **9**, 168-178.

Fletcher, P., and MacWhinney, B. 1995. *Handbook of child language.* Basil Blackwell, Oxford.

Fletcher, P. C., and Henson, R. N. 2001. Frontal lobes and human memory: insights from functional neuroimaging. *Brain* **124**, 849-881.

Frisson, L., and Pocock, S. J. 1992. Repeated measures in clinical trials: Analysis using mean summary statistics and its implications for design. *Stat. Med.* **11**, 1685-1704.

Friston K.J., Holmes A.P., Worsley K.J., Poline J.B., Frith C.D., and Frackowiak R.S.J. 1995. Statistical parametric maps: confidence intervals on p-values. *Hum. Brain Mapp.* **2**, 189-210.

Greenberg, J. H. 1963. Some Universals of Grammar with Particular Reference to the Order of Meaningful Elements. In *Universals of Language.* (J. H. Greenberg, Ed.) pp. 73-113. MIT Press, Cambridge, MA.

Greenfield, P. M., 1991. Language, tools and brain: The ontogeny and phylogeny of hierarchically organized sequential behavior. *Behav. Brain Sci.* **14**, 531-595.

Grodzinsky, Y. 2000. The neurology of syntax: Language use without Broca's area. *Behav. Brain Sci.* **23**, 1-71.

Jonides, J., Smith, E. E., Koeppe, R. A., Awh, E., Minoshima, S., and Mintun, M. A. 1993. Spatial working memory in humans as revealed by PET. *Science* **363**, 623-625.

Just, M. A., Carpenter, P. A., Keller, T. A., Eddy, W. F., and Thulborn, K. R. 1996. Brain activation modulated by sentence comprehension. *Science* **274**, 114-116.

Kayne, R. 1994. The Antisymmetry of Syntax. MIT Press, Cambridge, MA.

Kean, M. L. 1985. *Agrammatism.* Academic Press, New York.

Kim, K. H., Relkin, N. R., Lee, K. M., and Hirsch, J. 1997. Distinct cortical areas associated with native and second languages. *Nature* **388**, 171-174.

Klein, D., Milner, B., Zatorre, R. J., Meyer, E., and Evans, A. C. 1995. The neural substrates underlying word generation: a bilingual functional-imaging study. *Proc. Natl. Acad. Sci. USA* **92**, 2899-2903.

Kuhl, P. K. 2000. A new view of language acquisition. *Proc. Natl. Acad. Sci. USA* **97**, 11850-11857.

Levelt, W. J. M. 1989. *Speaking: from intention to articulation.* MIT Press, Cambridge, MA.

Marshuetz, C., Smith, E. E., Jonides, J., De Gutis, J., and Chenevert, T. L. 2000. Order information in working memory: fMRI evidence for parietal and prefrontal mechanisms. *J. Cogn. Neurosci.* **12(2)**, 130-144.

Meyer, M., Friederici, A. D., and von Cramon, D. Y. 2000. Neurocognition of auditory sentence comprehension: event related fMRI reveals sensitivity to syntactic violations and task demands. *Brain Res. Cogn. Brain Res.* **9**, 19-33.

Mohr, J. P., Pessin, M. S., Finkelstein, S., Funkestein, H. H., Duncan, G. W., and Davis, K. R. 1978. Broca aphasia. Pathologic and clinical. *Neurology* **28**, 311-324.

Moro, A. 2000. Dynamic Antisymmetry. MIT Press, Cambridge, MA.

Moro, A., Tettamanti, M., Perani, D., Donati, C., Cappa, S. F., and Fazio, F. 2001. Syntax and the brain: disentangling grammar by selective anomalies. *Neuroimage* **13**, 110-118.

Ni, W., Constable, R. T., Mencl, W. E., Pugh, K. R., Fulbright, R. K., Shaywitz, S. E., Shaywitz, B. A., Gore, J. C., and Shankweiler, D. 2000. An event-related neuroimaging study distinguishing form and content in sentence processing. *J. Cogn. Neurosci.* **12**, 120-133.

Nobre, A. C., Sebestyen, G. N., Gitelman, D. R., Mesulam, M.-M., Frackowiak, R. S. J., and Frith, C. D. 1997. Functional localisation of the system for visuospatial attention using positron emission tomography. *Brain* **120**, 515-533.

Oldfield, R. C. 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* **9**, 97-113.

Paulesu E., Frith C.D., and Frackowiak R.S. 1993. The neural correlates of the verbal component of working memory. *Nature* **362**, 342-345.

Perani, D., Dehaene, S., Grassi, F., Cohen, L., Cappa, S. F., Dupoux, E., Mehler, J., and Fazio, F. 1996. Brain processing of native and foreign languages. *Neuroreport* **7**, 2439-2444.

Perani, D., Paulesu, E., Sebastian Galles, N., Dupoux, E., Dehaene, S., Bettinardi, V., Cappa, S. F., Fazio, F., and Mehler, J. 1998. The bilingual brain. Proficiency and age of acquisition of the second language. *Brain* **121**, 1841-1852.

Raichle, M. E., Fiez, J. A., Videen, T. O., MacLeod, A. M. K., Pardo, J. V., Fox, P. T., and Petersen, S. E. 1994. Practice-related changes in human brain functional anatomy during non-motor learning. *Cereb. Cortex* **4**, 8-26.

Rizzolatti, G., Fogassi, L., and Gallese, V. 2001. Neurophysiological mechanisms underlying the understanding and imitation of action. *Nat. Rev. Neurosci.* **2(9)**:661-670.

Saffran, J. R., Aslin, R. N., and Newport, E. L. 1996. Statistical learning by 8-month-old infants. *Science* **274**, 1926-1928.

Seiler, H. 2000. *Language universals research : a synthesis.* Narr, Tübingen.

Stromswold K., Caplan D., Alpert N., and Rauch S. 1996. Localization of syntactic comprehension by positron emission tomography. *Brain Lang.* **52**, 452-473.

Talairach J., and Tournoux P. 1988. *Co-planar stereotaxic atlas of the human brain*. Thieme, Stuttgard.

Wildgruber, D., Kischka, U., Ackermann, H., Klose, U., and Grodd, W. 1999. Dynamic pattern of brain activation during sequencing of word strings evaluated by fMRI. *Brain Res. Cogn. Brain Res.* **7(3)**, 285-294.

Worsley, K. J., Marrett, S., Neelin, P., Vandal, A. C., Friston, K. J., and Evans, A. C. 1996. A unified statistical approach for determining significant signals in images of cerebral activation. *Hum. Brain Mapp.* **4**, 58-73.

Zatorre R.J., Evans A.C., Meyer E., and Gjedde A. 1992. Lateralization of phonetic and pitch discrimination in speech processing. *Science* **256**, 846-849.

Table 1. Groups of high and low proficiency in new syntactic rule usage.

	Subject	G	Subject	NG
High proficiency group	s13	98,4	s1	96,9
	s4	96,9	s8	95,3
	s2	95,3	s12	95,3
	s10	95,3	s5	95,3
	s9	92,2	s14	93,8
	s7	92,2	s10	90,6
	s3	90,6	s4	87,5
Low proficiency group	s14	89,1	s3	84,4
	s5	89,1	s11	82,8
	s11	89,1	s9	78,1
	s8	87,5	s7	76,6
	s12	87,5	s6	73,4
	s6	81,3	s13	73,4
	s1	73,4	s2	70,3

For each subject (s1-s14), accuracy scores averaged over the 4 blocks are given for grammatical rule (G) and non-grammatical rule (NG) usage, respectively (expressed as percentage of correct answers).

Table 2. Anatomical regions of significant activation in the experimental conditions as compared to their baseline.

Brain region	G-rule acquisition vs. baseline				NG-rule acquisition vs. baseline			
	x	y	z	Z	x	y	z	Z
L inferior frontal gyrus (BA 46)	-50	32	8	5.34	-44	46	4	5.06
L inferior frontal gyrus (BA 44)	-46	10	32	4.58				
L inferior frontal gyrus (BA 44)	-42	8	24	4.53				
L dorsal premotor area (BA 6)	-24	2	48	5.35				
L superior parietal lobule (BA 7)	-28	-58	52	7.22	-30	-54	60	4.77
L inferior parietal lobule (BA 40)	-40	-42	44	6.03	-48	-36	52	4.86
L precuneus (BA 7)	-22	-70	48	6.72	-28	-64	40	5.87
L angular gyrus (BA 39)	-30	-64	28	6.47				
L fusiform gyrus (BA 37)	-46	-56	-16	4.78	-44	-60	-16	4.69
anterior cingulate gyrus (BA 32)	2	22	40	5.10	6	34	28	5.63
R middle frontal gyrus (BA 46)					46	34	20	5.17
R inferior frontal gyrus (BA 46)	48	36	12	5.33	44	46	4	4.79
R inferior frontal gyrus (BA 44)	48	14	24	7.37	46	14	16	6.33
R inferior frontal gyrus (BA 47)	32	26	-4	4.96	36	26	-8	4.65
R dorsal premotor area (BA 6)	38	6	52	5.22	40	10	48	7.00
R superior parietal lobule (BA 7)					26	-58	60	6.95
R inferior parietal lobule (BA 40)	34	-58	40	7.94	34	-58	44	7.30
R precuneus (BA 7)	14	-66	44	6.68	14	-66	40	5.34

The stereotaxic coordinates (x,y,z) for significant voxels are given in mm together with the corresponding effect sizes (Z = Z scores).

Table 3. Behavioral data analyses: summary tables.

(A) Temporal changes during the acquisition of novel rules

	main effect	condition by block interaction	t-test : block 1	t-test : block 4
G-RA vs. RA-baseline	F(1,13) = 66.2 P < 0.0001	F(3,13) = 16.3 P < 0.0001	P < 0.0001	P = 0.07 *
NG-RA vs. RA-baseline	F(1,13) = 12.8 P = 0.003	F(3,13) = 9.2 P < 0.0001	P = 0.0004	P = 0.72 *
G-RA vs NG-RA	F(1,13) = 0.35 P = 0.56 *	F(3,13) = 1.08 P = 0.37 *		

(B) Effects of proficiency in novel rule usage

	main effect	condition by block interaction	t-test : block 1	t-test : block 4
G-RU vs. RU-baseline	F(1,13) = 19.6 P < 0.0001	F(3,13) = 3.9 P = 0.01	P = 0.002	P = 1 *
NG-RU vs. RU-baseline	F(1,13) = 11.3 P = 0.002	F(3,13) = 4.4 P = 0.006	P < 0.0001	P = 0.26 *
G-RU vs NG-RU	F(1,13) = 2.9 P = 0.10 *	F(3,13) = 1.5 P = 0.21 *		

* = not significant

Figure legends

Fig. 1: *Overall main effects of rule acquisition compared to the baseline.*

Activation maps (in colour) were projected on a rendered view of the smoothed canonical MNI brain template. **(A)** Regions of significant activation for the acquisition of G-rules. The grammar-specific activations in the left hemisphere (BA 44, 6 and 39) are indicated by arrows. **(B)** Regions of significant activation for the acquisition of NG-rules.

Fig. 2: *Temporal changes during acquisition of novel rules.*

 (A) The four average reaction time measurements corresponding to blocks 1-4 are plotted for the acquisition of G-rules (solid line), NG-rules (dash-dotted line) and the baseline (dotted line). **(B)** Areas increasingly more activated in time during G-rule than during NG- rule acquisition are superimposed (in red) on a single subject T1 image normalised to the MNI standard space. Stereotaxic coordinates (x, y, z in mm) and effect size (Z = Z score) of the activation peaks (indicated by arrows) are given in boxes. **(C)** The temporal interaction effect in the opercular portion of Broca's area (BA 44) is shown for two representative subjects. Filled bars indicate BOLD signal change percentage (amplitude of the hemodynamic response curve) in the four blocks for G-rule and NG-rule acquisition.

Fig. 3: *Effects of proficiency in novel rule usage.*

(A) The four average accuracy score measurements corresponding to blocks 1-4 are plotted for the usage of G-rules (solid line), NG-rules (dash-dotted line) and the baseline (dotted line). **(B)** Usage of novel G-rules, comparison between the groups of high and low proficiency

subjects: significant activation foci (in red) in Broca's area and the left ventral premotor area,

are superimposed on a sagittal slice of a single subject T1 normalised image.
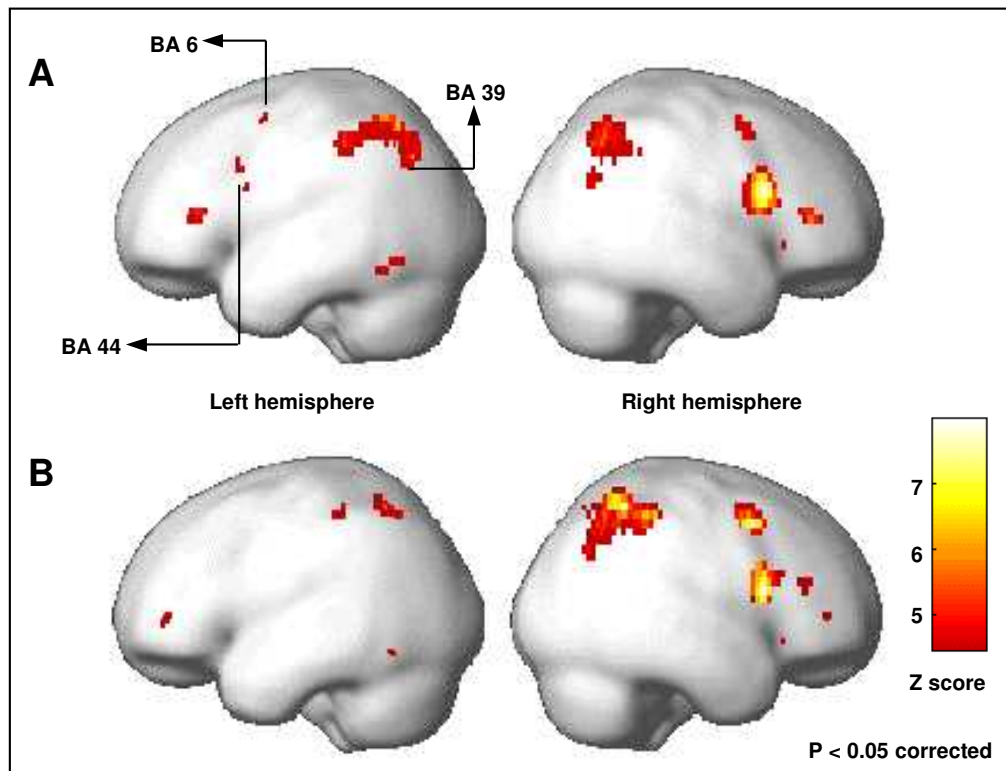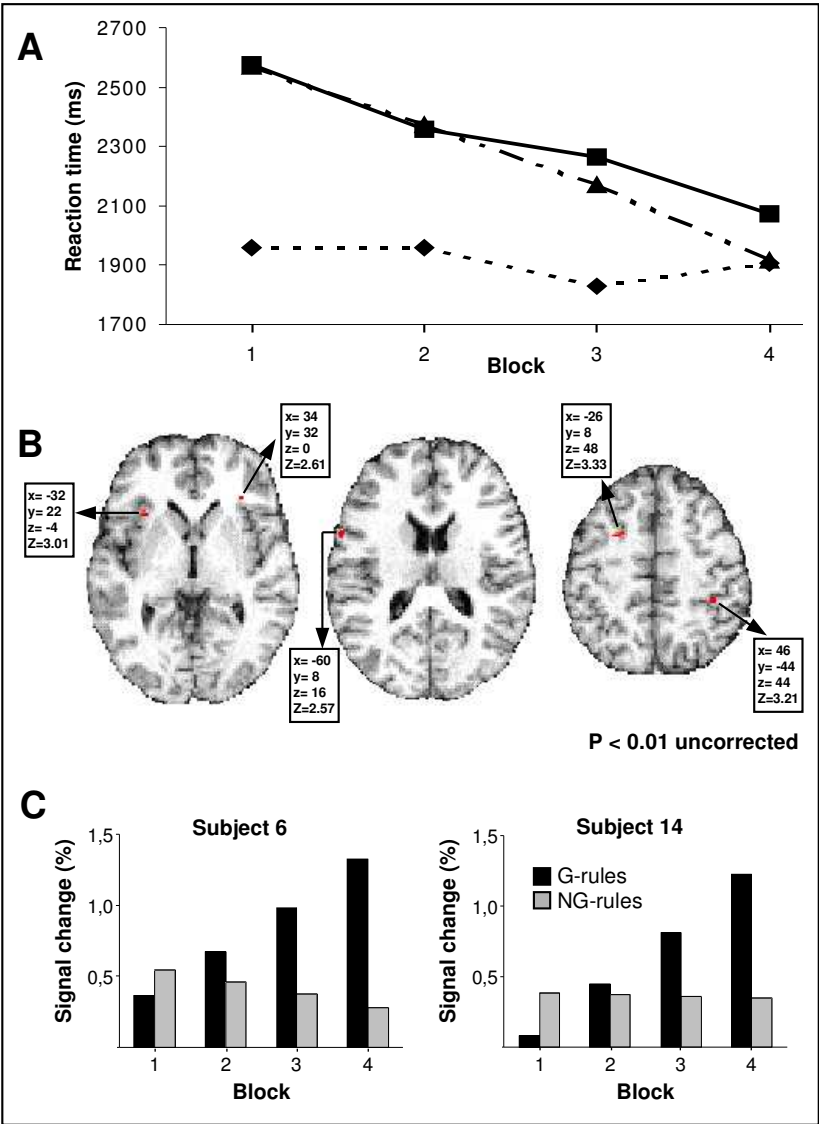
Fig. 1

Fig. 2

Fig. 3

A

Accuracy score (%)

Block

B

x = - 50

P < 0.001 uncorrected