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Autor: Tettamanti, Marco / Weniger, Dorothea
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The acquisition of natural language syntax: an fMRI study

Marco TETTAMANTI

Scientific Institute San Raffaele, c/o L.I.I.A., Via Fratelli Cervi 93,
I-20090 Segrate (Milano);
tettamanti.marco@hsr.it

Dorothea WENIGER

University of Zurich, Department of Neurology, Frauenklinikstrasse 26,
CH-8091 Zurich;
dorothea.weniger@usz.ch

Wie aus verhaltenspsychologischen Studien und experimentellen Untersuchungen mit funktioneller Bildgebung hervorgeht, werden die sprachlichen Verarbeitungsprozesse in einer Zweitsprache von unterschiedlichen Faktoren beeinflusst: Erwerbsalter, erworbene Sprachkompetenz, Intensität des Zweitsprachgebrauchs. Bislang nicht untersucht worden ist, wie eine natürliche Sprache in Echtzeit erworben wird, d.h. was für regionale Modulationen im Gehirn dem Spracherwerb zugrunde liegen. In der vorliegenden Untersuchung mit funktioneller Magnetresonanz Bildgebung wurde der Erwerb von hierarchisch gegliederten syntaktischen Strukturen mit dem Erwerb von nicht hierarchisch gegliederten syntaktischen Strukturen verglichen. Es konnte gezeigt werden, dass der Erwerb hierarchisch gegliederter syntaktischer Strukturen selektiv ein neuronales Netzwerk in der linken perisylvischen Hirnregion aktiviert, das auch das Broca Areal umfasst.

Introduction

The study of second language acquisition has been approached from a number of different perspectives. The fact that children acquire their native language with greater ease and more efficiently than adults learning a second language has led to the hypothesis that there must be a “critical period” for language acquisition. The hypothesis rests on the assumption that the age-related effects found in studies of second language acquisition (L2) are the result of maturational changes in the brain structures used to learn and process language. But it has been a matter of some debate whether the age-related effects on the acquisition of a L2 might not be brought about by the nature and extent of the interaction between a bilingual’s two language systems (Bialystok 1997; Bialystok & Miller, 1999; Flege et al., 1999; Birdsong & Molis, 2001).

As Flege and colleagues (1999) have pointed out in their behavioral study, age of acquisition is easily confounded with other variables that may influence L2 performance. These authors had native Korean participants, first exposed to English on arriving to the United States, repeat English sentences; the

participants' sentence productions were rated for overall degree of foreign accent. With increasing age of arrival stronger foreign accents were found; in addition, scores achieved in a grammaticality judgment task also decreased with increasing age of arrival. Further analyses of the data showed that the scores obtained in the grammaticality judgment tasks which tapped knowledge of the rule-based aspects of English morphosyntax varied as a function of the amount of education the participants had received; tasks testing for lexically based aspects of English morphosyntax led to scores that mirrored the degree to which the Korean participant used English. The authors argued that the age-related effects on morphosyntax are unlikely to have arisen from a maturationally defined critical period whereas the age-related effects on phonology may be due to maturational constraints, it being more likely that they resulted from changes in how the L1 and L2 phonological systems interact as the L1 system develops.

To investigate the hypothesis of a critical period in language acquisition Weber-Fox and Neville (1996) recorded the event-related brain potentials (ERPs) of adult Chinese-English bilinguals between the ages of 18 and 44 years as they read a randomized set of English sentences, half of the sentences being semantically and syntactically appropriate, half containing semantic anomalies or violating specific types of syntactic rules. Subject groupings were made. They were based on the age at which the bilingual participants began using English; the grouping ages were 1-3, 4-6, 7-10, 11-13, and >16 years. In response to semantic anomalies monolinguals have been found to display an increase in negativity that peaks at approximately 400 msec post-stimulus onset, known as the N400 effect. The 1-3, 4-6, and 7-10 bilingual groups showed a significant N400 effect in response to semantic anomalies; no differences for the peak latency of responses were found for these age groups compared to the monolinguals included in the study. However, the peak latencies of the N400 effect elicited in the 11-13 and >16 groups occurred later. Given the fact that these two groups differed with respect to the level of accuracy achieved in detecting semantic anomalies – the >16 group performing less accurately than the monolinguals – the similar shift in latency appears to reflect a slight slowing in processing rather than a difference in proficiency. The ERP response patterns obtained for syntactic processing suggest that the cerebral subsystems mediating different syntactic constructs are affected differently by delays in second language exposure. For example, the ERP response to phrase structure violations elicited in monolinguals is an enhancement of the N125 component at anterior regions of

the left hemisphere, followed by increased negativity between 300 and 500 msec maximal over temporal and parietal regions, and a large sustained positivity over all electrode locations beginning around 500 msec. With increased delays in second language exposure phrase structure processing is associated behaviorally with reduced judgment accuracies; electrophysiologically a reduced asymmetry is found for the effects of sentence type (control vs. phrase structure violation) on the N125 and N300-500 components and there is no 500-700 msec positivity shift. The changes in ERP asymmetries displayed by the bilingual groups suggest a reduced specialization of left hemisphere language processing subsystems and an increased right hemisphere involvement for specific types of syntactic constructs. Noteworthy is the finding that the participants exposed to English after the age of 16 years consistently performed less accurately than monolinguals and consistently showed the most extreme differences in ERP patterns compared with those observed in monolinguals.

The acquisition of vocabulary (semantics) appears to be less vulnerable to delays in second language exposure than the acquisition of linguistic structures related to syntactic processing. Furthermore, there is some evidence that the neural organization of the bilingual brain is also influenced by the proficiency a bilingual has attained in L2 (Perani et al., 1998; Chee et al., 2001). Wartenburger and colleagues (2003) investigated the effects which age of acquisition and proficiency level have on the neural organization of semantic and grammatical processing in L1 and L2 by using functional magnetic resonance imaging (fMRI). The Italian-German bilinguals in this study were grouped according to the age at which they began to be exposed to German (at birth or after 6 years of age) and their proficiency level in L2: subjects with early acquisition of L2 and high proficiency in L2 (EAHP), subjects with late acquisition of L2 and equally high proficiency in L2 (LAHP), and subjects with late acquisition of L2 and low proficiency in L2 (LALP). Subjects performed grammatical and semantic judgments task both in German and Italian; accuracy and reaction times were measured. None of the three groups differed in the level of performance achieved in the two judgments tasks in L1. The EAHP and LAHP group also showed no significant differences in their behavioral responses to the two judgment tasks in L2. But significant differences were found between the EAHP and LALP group for accuracy and reaction time in the grammatical as well as the semantic judgment task in L2. The LAHP group performed the two judgment tasks in L2 with significantly greater accuracy than the LALP group, but reaction times did

not differ between these two late acquisition groups. In agreement with the commonly held view that age of acquisition differentially influences the cortical representation of syntactic and semantic processing, the LAHP group was significantly less accurate and had significantly higher reaction times when judging the grammaticality of sentences in L2 than in L1; accuracy scores and reaction times did not differ when comparing L1 and L2 performance in semantic judgment tasks. In the LALP group reaction times were longer and accuracy scores lower in both the semantic and grammatical judgments in L2 compared to L1. As might not have been expected, the EAHP group displayed inferior accuracy in the semantic judgment in L1 compared to L2. The functional imaging data provide some support for the behavioral findings. Comparison of grammatical judgment in L2 to grammatical judgment in L1 showed no activation pattern differences in the EAHP group; but in both the LAHP and LALP group significant differences in activation pattern were found in language-related regions. The fact that the EAHP and the LAHP group showed no significant differences in their behavioral responses to the grammatical judgment task in L2 suggests that the neural representation of grammatical processing is more affected by age of acquisition than level of proficiency. However, the effect of age of acquisition was also demonstrated for semantic processing. Comparing the activation pattern elicited in semantic judgment tasks in L1 and L2 revealed significant activation differences in the LAHP group despite similar behavioral performance in the two languages. On the other hand, in both the LAHP and LALP group greater activation was elicited in semantic judgment tasks in L2 than in L1, without this difference being associated with inferior performance in the LAHP group. This finding indicates that proficiency does have a larger effect on the cortical representation of semantic processing.

In summary, second language processing can be influenced by age of acquisition, proficiency level and exposure to L2. Depending on the linguistic component being examined, electrophysiological and neuroimaging studies have shown second language processing to elicit different activation patterns in the brain than native language processing. However, little attention has been given thus far to issues pertaining to how the brain regions involved in the *acquisition* of a second language – in adulthood or at some developmental stage – are related to the regions involved in processing the native language. An 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. Some

syntactic rule formats, simple and logically possible, have never been found in human languages. 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 in the sentence”, even if it refers to fully identifiable lexical items, must be considered as “non-grammatical” since it has never been found in any human language grammar. Given that language rules follow a specific set of principles, what happens if the brain is confronted with a grammatical rule to learn? To investigate the neuroanatomical mechanisms involved in the acquisition of novel syntactic rules in adults we designed a functional magnetic imaging study in which the effects elicited by syntactic rules of a grammatical and a non-grammatical type were to be compared. We hypothesized that brain regions known to participate in syntactic processing would be involved more strongly in the acquisition of grammatical rules than in the acquisition of non-grammatical rules.

Materials and methods

Subjects

Fourteen 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 were monolingual Italian speakers from birth, with Italian-speaking parents. Right-handedness was verified using the Edinburgh Inventory (Oldfield, 1971).

Experimental design

Four experimental conditions were designed by combining two types of syntactic rule (grammatical (G) vs. non-grammatical (N G)) and two types of task (rule acquisition (RA) vs. rule usage (RU)). Two baseline conditions controlled for RA and RU tasks. The experiment thus consisted of six conditions: (1) RA-baseline: reading sentences following mother tongue syntax; (2) G-RA: reading sentences following a new syntactic rule of a grammatical nature; (3) NG-RA: reading sentences following a new syntactic rule of a non-grammatical nature; (4) RU baseline: detecting violations of native language syntax; (5) G-RU: detecting rule violations using the G-rule knowledge acquired (2); (6) NG-RU: detecting rule violations using the NG-rule knowledge acquired in (3).

Silent reading was required in both task conditions (i.e. rule acquisition and rule usage). In the RA-conditions subjects were asked to press a response button immediately after having read the sentence presented. In both the G-RA and NG-RA condition they were told that all sentences followed a new syntactic rule that had to be learned. In the RU-conditions a button press was required only if the syntactic structure of the sentence did not violate the rules set forth in the three acquisition conditions. Rules were never made explicit to the subjects before or during scanning sequences. Reaction times and accuracy scores were recorded.

Neuroimaging studies that have been concerned with the neural correlates of syntactic processing have often failed to control for the effects of sentential semantic processing (cf. Dapretto & Bookheimer, 1999; Newman et al., 2003). To eliminate confounding semantic effects open-class word-roots were replaced by pseudowords in all sentences. Italian phonology (as encoded in graphic form), inflections, function words and grammatical rules (with the exception of the novel syntactic rules introduced) were maintained.

For each type of syntactic structure (G vs. NG) two new rules were introduced: G-rule 1: The article must come immediately after the noun it refers to: *molte tille bilbavano daffio il*; G-rule 2: The auxiliary verb must come immediately after the main verb it refers to: *lo stoco artimando sta la bodova*; NG-rule 1: Articles must come immediately after the second word in the sentence: *molte tille il bilbavano raffio*; NG-rule 2: The auxiliary verb must come immediately after the third word in the sentence: *tutte le corade stanno si nagendo*. The baseline sentences followed Italian syntax: *molte tille bilbavano il daffio*. The full variety of Italian articles and auxiliary verbs was used. To avoid the adoption of a perceptual strategy function words having the same length as articles and auxiliaries were included. The linguistic status of the different items constituting a presented sentence had to be identified before syntactic regularities could be inferred. Sentences were balanced for both average number of syllables and average number of words.

The experiment comprised four scanning sequences, two sequences introducing a novel G-rule and two a novel NG-rule. Each of the four sequences had two parts both of which consisted of four successive alterations between rule acquisition and rule usage (the two task conditions). The one part (experimental) was devoted to the acquisition and usage of either a G-rule or an NG-rule; the other part was made up of alterations between the two baseline conditions. Each alteration formed a block and

within a block there were two sets of eight sentences, each set corresponding to one of the two conditions. This scheme resulted in a total of 512 sentences (4 sequences x 8 blocks x 16 sentences). The following example illustrates the scanning sequence: (RA-baseline)_{b1} – (RU-baseline)_{b1} – (RA-baseline)_{b2} – (RU-baseline)_{b2} – (RA-baseline)_{b3} – (RU-baseline)_{b3} – (RA-baseline)_{b4} – (RU-baseline)_{b4} – (G-RA)_{b1} – (R-RU)_{b1} – (G-RA)_{b2} – (G-RU)_{b2} – (G-RA)_{b3} – (G-RU)_{b3} – (G-RA)_{b4} – (G-RU)_{b4} - the b1 - b4 subscripts indicate the four blocks in each of the two parts constituting a sequence. Each subject underwent all four 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 were also presented in a balanced order across subjects. 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 given before positioning the subject in the scanner; the syntactic rules differed from those used in the experimental conditions.

Data acquisition

Data were acquired on a 1.5 T whole body scanner 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 cm², 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 250 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 interaction. The data of the four scanning sequences were pooled for each individual condition.

Functional MRI data processing and statistical analysis were performed with SPM99 (www.fil.ion.ucl.ac.uk). A detailed report of the data processing performed has been presented elsewhere (Tettamanti et al., 2002). 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 was performed (details in Tettamanti et al., 2002).

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. 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. Between group comparisons were calculated by two-sample t-tests using a random effect analysis. All the reported activations for these comparisons survived an uncorrected significance threshold of $p < 0.001$.

Results and discussion

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 Figure 1A and Figure 1B. With both rule types activations in a bilateral fronto-parietal network were found.

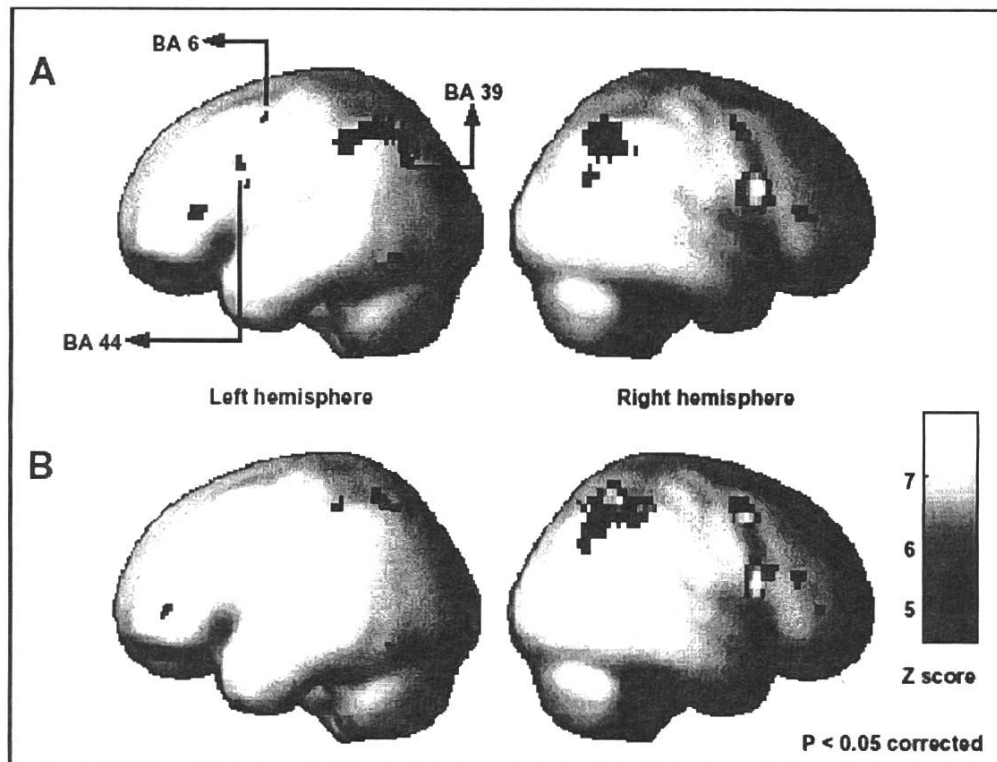


Figure 1. Overall main effects of rule acquisition compared to the baseline. Activation maps were projected on a rendered view of the smoothed canonical MNI brain template. (A) Regions of significant activation for the acquisition of G-rules. The grammar-specific activations in the left hemisphere are indicated by arrows. (B) Regions of significant activation for the acquisition of NG-rules.

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 in which the rules of an artificial grammar had to be learned (Fletcher et al., 1999), the syntactic properties of the artificial grammar differing 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.

Crucially and in agreement with our expectations 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 (BA6) 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 of Broca's area specifically found for the acquisition of grammatical rules is in agreement with the syntactic parsing functions attributed to this brain region and it is well known that lesions in the left premotor area can lead to what is known as Broca's aphasia. The acquisition of novel grammatical rules engages the neural network that specifically sustains the processing of the syntactic aspects of language.

In order to substantiate these differences we performed direct comparisons between the acquisition of novel G-rules and NG-rules. The left inferior frontal gyrus (BA 44/45) and the left ventral premotor area (BA 6) 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). NG-rules activated the right inferior frontal gyrus (BA 44/45) and the right superior parietal lobule (BA 7). Such findings confirm the specific role of Broca's area and the lateral premotor area in the acquisition of G-rules. In addition, greater activation of Wernicke's area (BA 22/39) in the G-rule than in the NG-rule condition is also in agreement with a number of neuroimaging studies investigating syntactic processing.

Our experimental paradigm not only allowed us to measure effects over the entire duration of the acquisition task, 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 (see Table 1). The interaction effects were analyzed by post-hoc paired t-test comparisons between experimental and baseline conditions in the first and last acquisition blocks: significant differences in the first block were no longer significant in the last block. The results of the ANOVA comparing G-RA and NG-RA were not significant.

	<i>main effect</i>	<i>Conditions by block interaction</i>	<i>t-test: first block</i>	<i>t-test: last block</i>
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. baseline	$F(1,13)=12.8$ $p=0.003$	$F(3,13)=9.2$ $p<0.001$	$p=0.0004$	$p=0.72^*$
G-RA vs. NG-RA	$F(1,13)=0.35$ $p=0.56^*$	$F(3,13)=1.08$ $p=0.37^*$		

Table 1: Changes in reaction times during the acquisition of novel rules (*=not significant)

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 (see Figure 2). 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 NG-rules. These were the opercular portion of Broca's 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). No brain regions 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 R-rules.

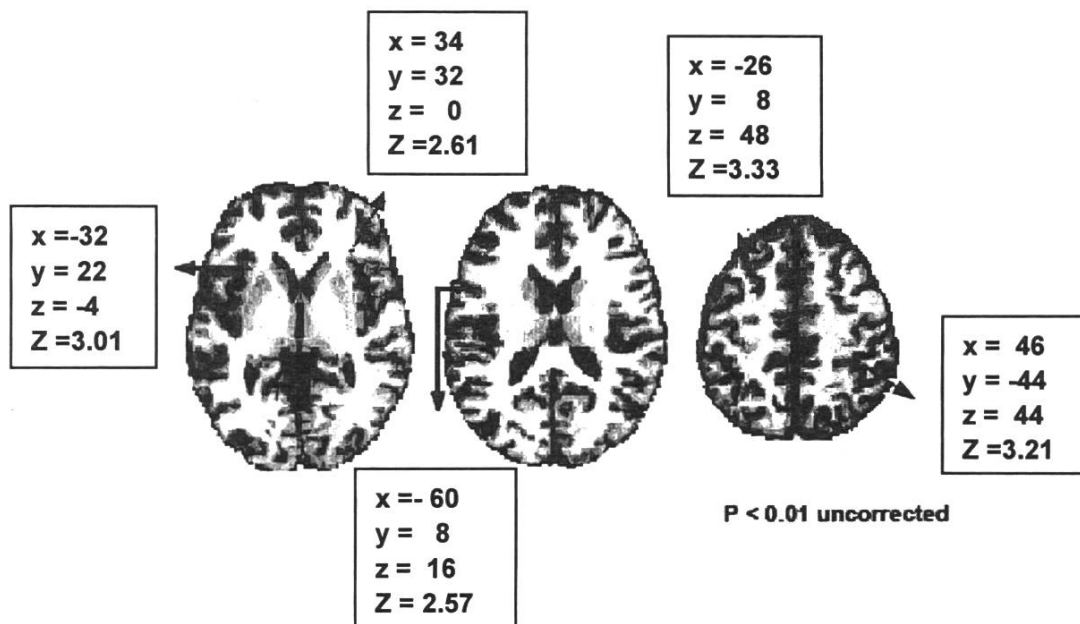


Figure 2. Areas increasingly more activated in time during G-rule than NG-rule acquisition superimposed on a single subject T1 image normalised to the MNI standard space. Stereotaxic coordinates (x,y,z in mm) and effect size (Z=Z score) of the activation peaks (indicated by arrows) are given in the boxes.

Intuitively one would expect to find a decrease rather than an increase of activation in perisylvian areas as the novel rules get mastered. As several studies have shown, automatic language processing does not engage perisylvian cortical areas (Bookheimer et al., 2000). Presumably in our experiment the monitored time interval of acquisition was too brief to allow for an automatization of grammatical rule processing. Although the novel grammatical rules have been successfully acquired their access still necessitates detailed syntactic parsing. In comparing the processing of

syntactic structures of high and low complexity Stromswold and colleagues (1996) found activations on the lateral surface of the opercular portion of Broca's area. The linear temporal increases of activation during rule acquisition in the present experiment were also found in this location. Processing syntactic complexity and non-automatized rules probably rely on verbal working memory functions. As has been demonstrated (Paulesu et al., 1993) the opercular portion of Broca's area is indeed associated with verbal working memory. These pieces of evidence suggest that the acquisition of novel syntactic rules in less automatized stages depends on a more lateral cortical portion of Broca's area than the one dedicated to syntactic processing in the native tongue.

As already pointed out above, most studies concerned with bilingual language processing have highlighted on the significance of such variables as proficiency level, age of acquisition and degree of exposure to L2. Neuroimaging studies have shown comparable levels of activation in left perisylvian areas elicited by L1 and L2 in highly proficient bilinguals (Perani et al., 1998; Chee et al., 2001; Wartenburger et al., 2003) and significantly different levels of activation in the same areas in low proficient bilinguals. The activation of left perisylvian regions thus seems to be modulated by the level of proficiency in the second language. This led us to hypothesize 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 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 (see Table 2). The interaction effects were analyzed by post-hoc paired t-test comparisons between experimental and baseline conditions in the first and last block. The results of the ANOVA comparing G-RU and NG-RU were not significant.

	<i>main effect</i>	<i>Conditions by block interaction</i>	<i>t-test: first block</i>	<i>t-test: last block</i>
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. baseline	F(1,13)=11.3 p=0.002	F(3,13)=44.4 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*		

Table 2: Changes in rule usage accuracy level (* = not significant)

In the fMRI data analysis between group statistics comparing high with low proficient subjects in G-rule and NG-rule usage were computed. During G-rule usage the high proficiency group activated Broca's area (BA 44) and the left ventral premotor area (BA 6) to a significantly greater extent than the low proficiency group. During NG-rule usage the high vs. low proficiency group comparison revealed a significantly activated focus in the left cerebellar hemisphere. Thus, competent usage of G-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

The study demonstrates a selective and robust participation of Broca's area in the acquisition of novel G-rules as opposed to NG-rules. The data represent a contribution to the ongoing discussions pertaining to the cerebral mechanisms that underlie adult L2 acquisition: the gain of competence for novel and selected linguistic features appears to be closely associated with variations of activity in exactly those perisylvian brain regions implicated in the processing of the corresponding linguistic aspects. In the early stages of language acquisition the processing of novel linguistic structures involves lateral cortical aspects of Broca's area that support less automatic processes. Our data show that a neuroanatomical network comprising Broca's area subserves language acquisition in adults; it is well possible that such a network is not specific to language acquisition but also found to be involved when the task calls for hierarchical processing strategies.

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