

Unified inflectional processing of regular and irregular verbs: a PET study

M. Sach,^{1,CA} R. J. Seitz and P. Indefrey²

University Hospital Düsseldorf, Department of Neurology, Moorenstr. 5, 40225 Düsseldorf, Germany; ²Max Planck Institute for Psycholinguistics, Postbus 310, 6500 AH Nijmegen; F.C. Donders Centre for Cognitive Neuroimaging, Postbus 9101, 6500 HB Nijmegen, Netherlands
¹Present Address: University Hospital Hamburg Eppendorf, Department of Neurology, Martinistr. 52, 20246 Hamburg, Germany

^{CA}Corresponding Author: sach@uke.uni-hamburg.de

Received 19 November 2003; accepted 3 December 2003

DOI: 10.1097/01.wnr.0000113529.32218.92

Psycholinguistic theories propose different models of inflectional processing of regular and irregular verbs: dual mechanism models assume separate modules with lexical frequency sensitivity for irregular verbs. In contradistinction, connectionist models propose a unified process in a single module. We conducted a PET study using a 2 × 2 design with verb regularity and frequency. We found significantly shorter voice onset times for regular verbs and high

frequency verbs irrespective of regularity. The PET data showed activations in inferior frontal gyrus (BA 45), nucleus lentiformis, thalamus, and superior medial cerebellum for both regular and irregular verbs but no dissociation for verb regularity. Our results support common processing components for regular and irregular verb inflection. *NeuroReport* 15:533–537 © 2004 Lippincott Williams & Wilkins.

Key words: Language; Morphology; PET; Positron emission tomography; Verb inflection

INTRODUCTION

An important issue in the research of language is the nature of mental computation. Does mental computation depend on an internally organised system of symbol-processing rules, such as those underlying grammar or is it rather represented in a neural system without symbolic rules? The mental processing of regular (cook-cooked) and irregular (sing-sang) verbs is a crucial point of this debate. Different models exist to explain inflectional processing in the human brain: connectionist models propose a single process model with a unified inflectional system in which regular and irregular inflections are represented in the same neural network and handled in the same way [1,2]. Connectionist models predict that regular and irregular verb forms are computed in the same areas of the brain, because identical mechanisms are presumed to be active during the production of both [3]. In contrast, dual process models postulate that regular and irregular verb production is handled by separate cognitive mechanisms. They assume a symbolic rule-based system by the mental grammar for the processing of regular words [4]: for instance, regular past tense forms are generated on-line by a traditional symbolical rule of the grammar that combines the suffix -ed (German: -te) with the verb stem (cook-cooked, German: kochen-kochte). In contrast, dual process models postulate a lexical storage in an associative memory system (the mental lexicon) for irregular verbs [5,6]. Lexical decision times have been shown to be affected by word frequency and are shorter for high frequency participles of irregular verbs than for those of low frequency [6]. These latency differences in

retrieval are caused by a memory effect: as memory traces become stronger with additional exposures, high frequency entries in the mental lexicon can be accessed faster than low frequency ones. Hence, irregular verb forms, represented as memorised items in the mental lexicon [5], should be strongly affected by frequency effect of the associative memory, whereas regular forms should not [6,7]. Access to irregular verb forms is based on search processes for lexical entries, whereas affiliation-based forms, like regular verbs, are typically computed on-line [6]. Hence, dual process models imply a significant interaction between verb regularity and verb frequency: regular verbs are inflected independently of their frequency in spoken language, while irregular verbs of low frequency are processed more slowly than those of higher frequency [6,7]. Because the inflection of regular and irregular verbs is computed by different mechanisms different neuronal activations for regular and irregular verbs are posited. According to dual system models, the regular rule would be predicted to involve left frontal lobe activity, since the left frontal lobe is typically involved in grammatical processing [8]. If irregular verb forms are stored in an associative memory with lexical retrieval, activity in the temporal lobe would be expected [9]. As a neural implementation of dual mechanism models, Ullman *et al.* [4] propose a distinction into a declarative memory for irregular verbs and a procedural memory for regular verbs. In this framework, the mental lexicon depends on declarative memory and is rooted in the temporal lobe and right cerebellum, whereas the mental grammar involves procedural memory and is located in the

frontal cortex and basal ganglia. We conducted a PET experiment using regular and irregular German verbs of various frequencies in language to elucidate a possible differential sensitivity to word frequency during the production of inflectional past tense and participle forms. Our hypotheses were guided by the assumptions of dual process models: (a) an interaction effect in voice onset times and neural activation between verb regularity and verb frequency and (b) different neuronal activations for regular and irregular inflection.

MATERIALS AND METHODS

Subjects: Twelve native right-handed German speaking volunteers (six males and six females, mean (\pm s.d.) age 25.3 ± 2.9 years) participated in the study and were tested for handedness using the Edinburgh inventory. All subjects were free of neurological or other diseases. They either had normal or corrected to normal vision. All participants provided written informed consent for the study which was approved by the local ethics committee.

Experimental paradigm: During four PET scans, we presented German infinitive verb forms, which had to be inserted with appropriate inflection of past tense and participle forms into a neutral sentence frame. German infinitive verb forms always consist of the stem of the verb and the suffix -en. In two further PET scans, we presented verbs already in their correct inflected form which the subjects merely had to insert into the sentence frame (baseline condition). The sentence frames required solely past tense (Er kochte etwas; He cooked something.) or participle formation (Er hat etwas gekocht; He has cooked something.) This information was given to the subjects in the instruction and explained in detail. The subjects were asked to say the whole sentence including the inflected form aloud. Past tense and participle sentences were randomised within scans to avoid response strategies. Additionally, we randomised inflectional condition and baseline condition over the six scans. In a 2×2 factorial design, we varied verbs between scans along the dimensions regularity (regular/irregular), and frequency (high/low). High and low frequency verbs were classified according to CELEX database (Table 1). Sentence frames were shown on a monitor for 1 s. Following an interval of 500 ms, we presented the verb for 600 ms and recorded response sentences on DAT tape (Sony TCD-D10). The sentences were analysed for correctness and voice onset time (VOT, measured from the appearance of the verb on the monitor screen) using the XWAVES speech-processing package. Response onsets after 1000 ms and incorrect inflections were counted as errors and excluded from the VOT analysis. In the PET experiment, the combinations of regularity and frequency had to be presented in separate conditions due to the block design. In a prescanning reaction time study, we

therefore presented the same stimuli in non-blocked randomised order to investigate whether the block design altered stimulus processing in morphological production of regular and irregular verbs.

Image data acquisition: During six PET scans, subjects were lying still with their heads stabilised by individually moulded head supports. The scan sequence was varied across subjects. The rCBF (regional cerebral blood flow) was measured for a period of 40 s after i.v. injection of [^{15}O]butanol (~ 1.4 GBq/scan). Bolus injections were performed into the right brachial vein and immediately flushed with 10 ml saline solution. Prior to emission scans, a transmission scan was obtained for attenuation correction using a rotating ^{68}Ge pin source. The eight-ring PET camera (GE/Scanditronix PC 4096-15 WB, General Electrics, Uppsala, Sweden) had a spatial resolution of 4.6 mm in plane, and a slice distance of 6.5 mm. The PET image slices were reconstructed with a Hanning filter to an effective image resolution of 9.0 mm.

We also acquired high-resolution structural T_1 -weighted MR images using a volumetric FLASH sequence.

Data analysis: Voice onset times and errors were analysed using a 3×2 omnibus MANOVA for repeated measures with the within-subject factors condition (levels: regular, irregular and insertion) and frequency (levels: high and low spoken frequency). To assess the effects of regularity and frequency only for the scans, in which verb forms were actively inflected, we subsequently conducted a 2×2 repeated-measures MANOVA with the factors regularity (regular *vs* irregular verbs) and frequency.

For imaging data analysis we used statistical parametric mapping (SPM99). The image volumes were realigned, normalised into the common stereotactic Montreal Neurological Institute (MNI) space, smoothed with a Gaussian filter of 20 mm FWHM, and corrected for residual within- and between-subject global CBF variation by analysis of covariance. We performed statistical tests on single activation-control contrasts as well as conjunctions of two and four activation-control contrasts. Conjunctions were masked with the set of corresponding single contrasts ($p < 0.05$). Based on the findings of Jaeger *et al.* [5], we predicted activation of three regions (left inferior and superior frontal gyri, left precuneus) and report clusters of activated voxels exceeding a significance threshold of $p < 0.001$ (uncorrected). For all other regions we report clusters of activated voxels exceeding a significance threshold of $p < 0.05$ (corrected).

RESULTS

Behavioural data: Voice onset times (VOT) were similar to those obtained in a preceding reaction time experiment

Table 1. CELEX database frequencies for mean written infinitive (stimulus) verb form and mean spoken past/participle (target) verb form (CELEX-lexical database for German, Centre for Lexical Information, Max-Planck Institute for Psycholinguistics, Nijmegen, Netherlands).

Stimulus and target verbs	Regular		Irregular		Insertion	
	High	Low	High	Low	High	Low
Infinitive	3891	14.8	572.5	21.3	428.2	15.8
Past/participle	21.3	0.6	26.4	0.7	33.8	0.3

using identical but randomised stimuli, indicating that the blocked design did not alter inflectional processing (Fig. 1). In the omnibus MANOVA, we found a significant main effect of the factor condition ($F(2,6) = 17.52$; $p < 0.0001$). Results from the 2×2 MANOVA showed a significant main effect of regularity ($F(1,8) = 37.26$; $p < 0.0001$) with faster VOTs for regular than for irregular verbs and a significant main effect of frequency ($F(1,8) = 5.27$; $p = 0.042$) with faster VOTs for high frequency verbs. There was no significant interaction of the two factors.

Error data: The number of error trials was overall low. The percentages of errors were 0.833 ± 1.946 for regular/high frequency inflection, 6.250 ± 8.292 for regular/low frequency inflection, 4.605 ± 6.559 for irregular/high frequency inflection, 7.917 ± 7.217 for irregular/high frequency inflection, 2.105 ± 3.364 for high frequency insertion, and 2.522 ± 4.004 for low frequency insertion. The omnibus MANOVA showed significant main effects of condition ($F(2,6) = 3.51$; $p = 0.048$) and frequency ($F(1,6) = 6.68$; $p = 0.025$) but no significant interaction. The 2×2 MANOVA showed a main effect of frequency ($F(1,8) = 6.66$; $p = 0.026$) with higher error rates for low frequency verbs but no significant main effect of regularity and no significant interaction between the two factors.

PET data: A conjunction analysis which tested for hemodynamic effects of inflectional processing (regular and irregular verbs of high and low spoken frequency) *vs* baseline condition (insertion of inflected high and low spoken frequency verb forms) revealed significant rCBF increases in the left inferior frontal gyrus, Brodmann's area (BA) 45, the right nucleus lentiformis and thalamus, and the superior medial cerebellum (Fig. 2). A conjunction analysis comparing inflectional processing of high and low frequency regular verbs to insertion showed a significant rCBF increase only in the right nucleus lentiformis and thalamus (16, -20, -4). A conjunction analysis comparing inflectional processing of high and low frequency irregular verbs to insertion showed a significant rCBF increase only in the

medial cerebellum (4, -52, -26). Reverse comparisons of baseline *vs* regular or irregular inflection showed no significant rCBF increases. We did not find any significant rCBF differences in three comparisons (high frequency, low frequency, conjunction of high and low frequency) between regular and irregular verb inflection. Similarly, there were also no significant rCBF differences in three comparisons (regular, irregular, conjunction of regular and irregular) between high frequency and low frequency inflection. Finally, there were no significant interactions between regularity and frequency.

DISCUSSION

In a factorial design, we manipulated both regularity and frequency of past tense and participle verb forms. In line with previous studies [5], we found longer VOTs for irregular compared to regular verb inflection. We also observed an effect of verb frequency both on VOTs and error rates. Crucially, neither VOTs nor error rates showed the predicted interactions between regularity and frequency. Thus, the effect of the spoken frequency of the verb form to be produced did not significantly differ between regular and irregular verbs, suggesting a similar processing mechanism.

Regarding the PET data, we found rCBF increases in the right nucleus lentiformis and thalamus in regular verb inflection *vs* insertion and in the medial cerebellum in irregular verb inflection *vs* insertion. The conjunction analysis testing for inflectional processing *vs* verb insertion revealed rCBF increases in the right nucleus lentiformis, thalamus, in the medial cerebellum and in the inferior frontal gyrus (BA 45). Nucleus lentiformis, thalamus and midline cerebellum have been reported to be involved in the motor act of articulation [10] and might therefore be regarded as the common final route of inflectional processing. The fact that these regions were stronger activated during regular and irregular verb inflection than during verb insertion suggests a role beyond articulation because both verb production and insertion required articulatory movements from the subjects and this motor activation was cancelled out in our differential contrast. Basal ganglia are involved in grammar processing and project through the thalamus to cortical regions, in particular in the frontal cortex [4]. fMRI studies indicate involvement of the putamen in lexical-semantic processing [11]. Pathology of the putamen and thalamus has also been reported in association with aphasic symptoms [12]. Patients with anterior thalamic infarctions in either hemisphere present symptoms of transcortical motor aphasia [13].

The posterior portion of the left inferior frontal gyrus containing the pars opercularis and the pars triangularis has been assigned to Broca's area [14,15]. Its cytoarchitectonic areas comprise BA 44 and 45 [16,17] matching our findings in the left inferior frontal gyrus (BA 45). A recent study combining probabilistic maps of BA 44 and 45 with PET activation found involvement of BA 45 in modality-independent aspects of language generation whereas BA 44 was activated in oral motor control [18]. It is proposed that BA 45 is involved in lexical selection [19] as well as in grammatical processing [8]. Neuroimaging studies have found that neuronal activations in the left frontal cortex are often accompanied by similar increases in right cerebellar regions [20] in speech activation [21] and verbal working

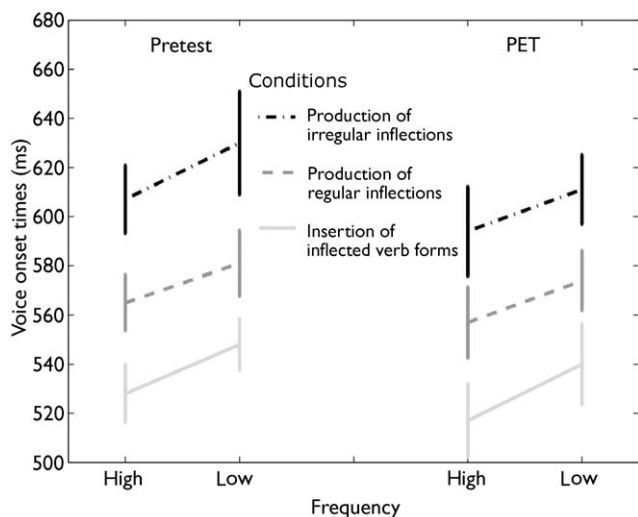


Fig. 1. Mean (\pm s.e.) voice onset times with standard error of the mean for pretest (randomised stimulus presentation) and PET experiment (blocked stimulus presentation).

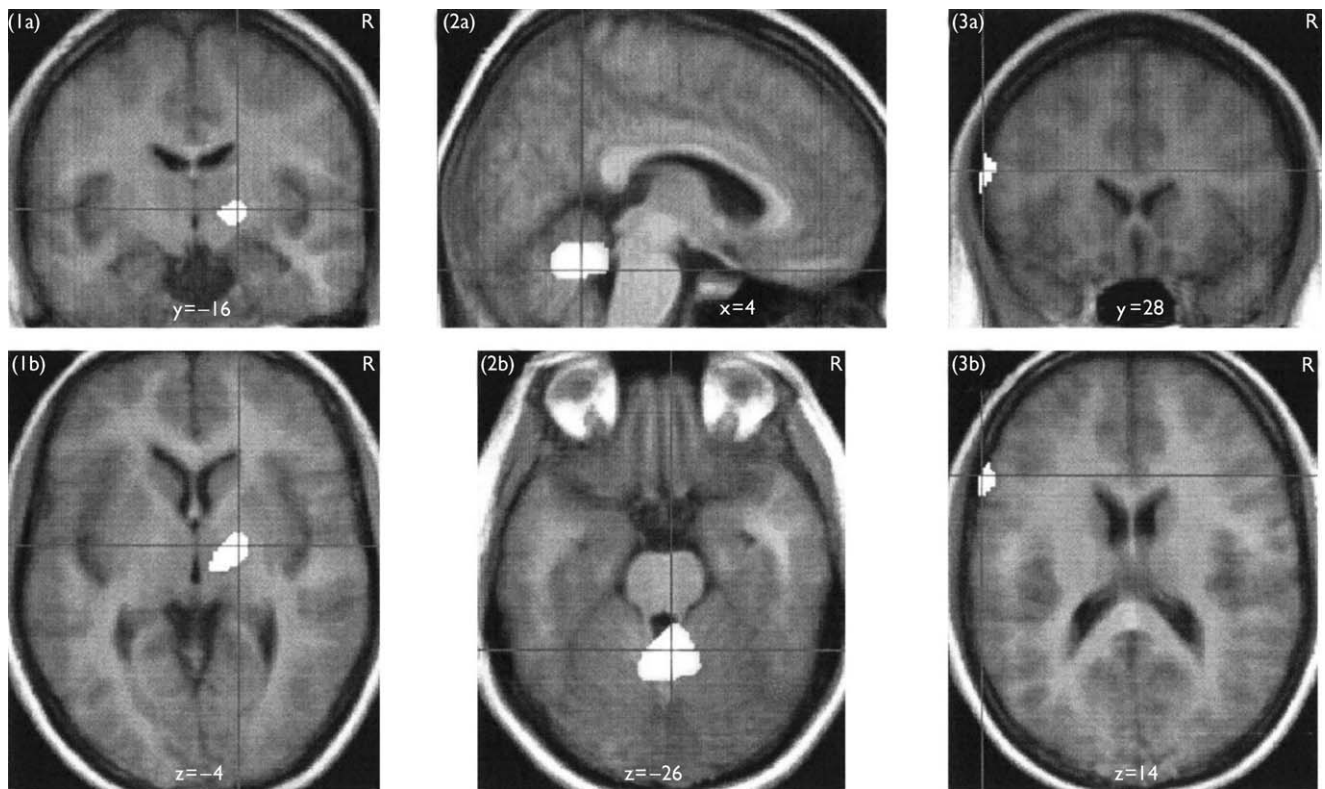


Fig. 2. Statistical results from the conjunction analysis testing for common activations of regular and irregular inflections vs insertion ($p < 0.05$, corrected) superimposed on the average T_1 -weighted MR image. Crosshairs indicate the peak voxel within the significantly activated cluster with voxel-level Z-values and MNI-coordinates reported below. **(1a,b)** Right nucleus lentiformis and thalamus (16, -16, -4), $Z = 4.72$ ($p = 0.005$, corrected). **(2a,b)** Superior medial cerebellum (4, -50, -26), $Z = 4.95$ ($p = 0.002$, corrected). **(3a,b)** Left inferior frontal gyrus, BA 45 (-62, 28, 14), $Z = 4.12$ ($p = 0.058$, corrected).

memory tasks [22]. The anatomical substrate for this cerebellar diachisis is the fronto-ponto-dento-cerebellar tract [21]. The fact that the cerebellum also sends anatomical pathways to the thalamus which is connected to the nucleus lentiformis [23] is in accordance with the subcortical rCBF increases we found in the right hemisphere. Patients with cerebellar lesions display articulatory deficits with slowed speech tempo. Additionally, silent repetition of syllables at high rates exhibit cerebellar activation within Larsell's H VI (i.e. representation of tongue and lip) which is located more lateral to the activation found by us [24]. Functional imaging studies have also suggested a non-motor involvement of the right cerebellum in verb generation and verbal association [25]. Neuronal activation in the right cerebellum is also posited by the declarative model [4]. Additionally, we found rCBF increases in the nucleus lentiformis, thalamus and Broca's area which agree well with the procedural model [4].

Our PET data do not support the distinction into a declarative memory for irregular verbs and a procedural memory for regular verbs [4], since both productions of regular and irregular verb forms activated the right nucleus lentiformis and thalamus, the medial cerebellum, and Broca's area. Although separate analyses for regular and irregular verbs suggested a pattern along the lines of Ullman *et al.* [4] with nucleus lentiformis activation found for regular verbs and cerebellar activation for irregular verbs, this difference was not significant in the direct

comparison of regular *vs* irregular verb inflection and vice versa. This result differs from three previous studies reporting distinct activation patterns for regular and irregular inflection [3–5]. However, in Jaeger *et al.* [5] the claims about differences between regular and irregular processing were not based on direct comparisons, but on different activation patterns compared with baseline. Furthermore, most of the reported areas did not survive a corrected significance threshold. Ullman *et al.* [4] and Dhond *et al.* [3] report activation differences between regular and irregular inflection in direct comparisons. However, in both studies such differences were found in regions that were activated by regular as well as irregular processing compared to baseline. In sum, our data agree with previous studies in that there is a common network of brain areas activated by both regular and irregular verb inflection. This network seems to comprise the left inferior frontal gyrus (all studies), the basal ganglia (our data, [4]), and the left superior temporal lobe [3,4]. This pattern of results speaks against distinct and specific neural correlates of regular and irregular inflection. In contrast to previous studies [3–5] we also varied the spoken frequency of the verb forms to be produced. This design allowed us to test a prediction of dual mechanism models: hemodynamic effects reflecting an interaction between verb regularity and frequency. We observed neither a significant main effect of frequency nor a significant neuronal interaction of frequency with regularity.

CONCLUSION

We had no evidence for interaction effects predicted by dual mechanism models both at a behavioural and a neural level. Common neural activations as well as similar behavioural frequency effects support shared processing components for regular and irregular verb inflection.

REFERENCES

- Rumelhart DE and McClelland JL. On learning the past tenses of English verbs. In: *Parallel Distributed Processing: Explorations in the Microstructure of Cognition*. Cambridge, MA: MIT Press; 1986, pp. 216–271.
- Joanisse Mf and Seidenberg MS. Impairments in verb morphology after brain injury: a connectionist model. *Proc Natl Acad Sci USA* **96**, 7592–7597 (1999).
- Dhond RP, Marinkovic K, Dale AM, Witzel T and Halgren E. Spatiotemporal maps of past-tense verb inflection. *Neuroimage* **19**, 91–100 (2003).
- Ullman MT. A neurocognitive perspective on language: the declarative/procedural model. *Nature Rev Neurosci* **2**, 717–726 (2001).
- Jaeger JJ, Lockwood AH, Kemmerer DL, Van Valin RD, Murphy BW and Khalak HG. A positron emission tomographic study of regular and irregular morphology in English. *Language* **72**, 451–497 (1996).
- Clahsen H. Lexical entries and rules of language: a multidisciplinary study of German inflection. *Behav Brain Sci* **22**, 991–1060 (1999).
- Pinker S. Rules of language. *Science* **253**, 530–535 (1991).
- Musso M, Moro A, Glauche V, Rijntjes M, Reichenbach J, Buchel C and Weiller C. Broca's area and the language instinct. *Nature Neurosci* **6**, 774–781 (2003).
- Howard D, Patterson K, Wise R, Brown WD, Friston K, Weiller C and Frackowiak R. The cortical localization of the lexicons. Positron emission tomography evidence. *Brain* **115**, 1769–1782 (1992).
- Price CJ, Wise RJ, Warburton EA, Moore CJ, Howard D, Patterson K *et al*. Hearing and saying. The functional neuro-anatomy of auditory word processing. *Brain* **119**, 919–931 (1996).
- Kotz SA, Cappa SF, von Cramon DY and Friederici AD. Modulation of the lexical-semantic network by auditory semantic priming: an event-related functional MRI study. *Neuroimage* **17**, 1761–1772 (2002).
- Kuljic-Obradovic DC. Subcortical aphasia: three different language disorder syndromes? *Eur J Neurol* **10**, 445–448 (2003).
- Ghika-Schmid F and Bogousslavsky J. The acute behavioral syndrome of anterior thalamic infarction: a prospective study of 12 cases. *Ann Neurol* **48**, 220–227 (2000).
- Broca MP. Remarques sur le siege de la faculte du langage articule, suivies d'une observation d'aphemie (Perte de la Parole). *Bull Mem Soc Anat Paris* **36**, 330–357 (1861).
- Foundas AL, Eure KF, Luevano LF and Weinberger DR. MRI asymmetries of Broca's area: the pars triangularis and the pars opercularis. *Brain Lang* **64**, 282–296 (1998).
- Uylings HB, Malofeeva LI, Bogolepova IN, Amunts K and Zilles K. Broca's language area from a neuroanatomical and developmental perspective. In: Brown CM and Hagoort P (eds). *Neurocognition of Language*. Oxford: Oxford University Press; 1999, pp. 319–336.
- Amunts K, Schleicher A, Burgel U, Mohlberg H, Uylings HB and Zilles K. Broca's region revisited: cytoarchitecture and intersubject variability. *Comp Neurol* **412**, 319–341 (1999).
- Horwitz B, Amunts K, Bhattacharyya R, Patkin D, Jeffries K, Zilles K *et al*. Activation of Broca's area during the production of spoken and signed language: a combined cytoarchitectonic mapping and PET analysis. *Neuropsychologia* **41**, 1868–1876 (2003).
- Fiebach CJ, Friederici AD, Muller K and von Cramon DY. fMRI evidence for dual routes to the mental lexicon in visual word recognition. *J Cogn Neurosci* **14**, 11–23 (2002).
- Desmond JE, Gabrieli JD and Glover GH. Dissociation of frontal and cerebellar activity in a cognitive task: evidence for a distinction between selection and search. *Neuroimage* **7**, 368–376 (1998).
- Borbely K, Gjedde A, Nyary I, Czirkak S, Donauer N and Buck A. Speech activation of language dominant hemisphere: a single-photon emission computed tomography study. *Neuroimage* **20**, 987–994 (2003).
- Fiez JA. Cerebellar contributions to cognition. *Neuron* **16**, 13–15 (1996).
- Thach WT. What is the role of the cerebellum in motor learning and cognition? *Trends Cogn Sci* **2**, 331–337 (1998).
- Wildgruber D, Ackermann H and Grodd W. Differential contributions of motor cortex, basal ganglia, and cerebellum to speech motor control: effects of syllable repetition rate evaluated by fMRI. *Neuroimage* **13**, 101–109 (2001).
- Raichle ME, Fiez JA, Videen TO, MacLeod AM, Pardo JV, Fox PT *et al*. Practice-related changes in human brain functional anatomy during nonmotor learning. *Cerebr Cortex* **4**, 8–26 (1994).

Acknowledgements: We thank Professor Herzog and W. Hamkens, Research Centre Jülich, for their continuous support. This study was supported by the Sonderforschungsbereich I94 of the Deutsche Forschungsgemeinschaft.