Cerebellar Responses Evoked by Nociceptive Leg Withdrawal Reflex as Revealed by Event-Related fMRI

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Dimitrova, A., F. P. Kolb, H.-G. Elles, M. Maschke, M. Forsting, H. C. Diener, and D. Timmann. Cerebellar responses evoked by nociceptive leg withdrawal reflex as revealed by event-related fMRI. J Neurophysiol 90: 1877–1886, 2003. First published April 17, 2003; 10.1152/jn.00053.2003. The aim of the present study was to examine nociceptive leg withdrawal reflex–related areas in the human cerebellum using event-related functional brain imaging (fMRI). Knowledge about cerebellar areas involved in unconditioned limb withdrawal reflex control has some relevance in understanding data of limb withdrawal reflex conditioning studies. Sixteen healthy adult subjects participated. Nociceptive leg withdrawal reflexes were evoked by electrical stimulation of the left tibial nerve behind the medial malleolus. An event-related fMRI paradigm was applied with a total of 30 stimuli being delivered pseudorandomly during 500 consecutive MR scans. Surface electromyographic (EMG) recordings were performed from the left anterior tibial muscle. Only trials with significant reflex EMG activity were used as active events in fMRI statistical analysis. The specified contrasts compared the active event condition with rest. Leg withdrawal reflex–related areas were located within the vermis, paravermis, and lateral posterior cerebellar hemispheres bilaterally. Vermal and paravermal areas in lobules III/IV in the anterior lobe and in lobule VIII in the posterior lobe agree with the cerebellar representation of climbing and mossy fiber hindlimb afferents and voluntary leg movements. They are likely related to efferent modulation of the leg withdrawal reflex and/or sensory processing of afferent inputs from the reflex and/or the noxious stimulus. Additional activation within vermal lobule VI and hemispheric lobules VI/V Crus I may be related to other pain-related processes (e.g., facial grimacing, fear, and startlelike reactions).

I N T R O D U C T I O N

Classical conditioning of specific aversive reactions has frequently been used to study the role of the cerebellum in motor learning in both animals and humans. Numerous cerebellar studies have investigated classical conditioning of the eyelid reflex response (for reviews see Bloedel and Bracha 1995; Mauk et al. 2000; Thompson et al. 1997; Woodruff-Pak and Steinmetz 2000a, b; Yeo and Hesslow 1998). Other studies have examined involvement of the cerebellum in conditioning of the nociceptive limb withdrawal reflex (Apps and Lee 2002; Kolb et al. 1997; Timmann et al. 1996, 2000; Voneida 2000). To understand the role of the cerebellum in reflex conditioning knowledge about the cerebellar areas involved in control of the unconditioned responses has some relevance. First, lesion studies are likely to show the clearest deficits in learning if all areas involved in unconditioned reflex control are affected (Yeo and Hesslow 1998). Likewise, one possible reason for controversial results of lesion studies may be that cerebellar cortical areas involved in unconditioned reflex control are affected to various extents. In addition, demonstration of cerebellar areas involved in control of unconditioned reflexes raises the controversial issue of impaired motor performance (i.e., impaired unconditioned reflexes) and its possible relation to deficits in conditioning (pro: Harvey et al. 1993; Welsh and Harvey 1989; contra: Steinmetz et al. 1992).

Cerebellar areas involved in control of unconditioned eyeblink response have been investigated in detail in animals (Hesslow 1994a, b; Morcuende et al. 2002; Pellegrini and Evinger 1997) and humans (Dimitrova et al. 2002a). Knowledge about cerebellar areas involved in control of the nociceptive limb withdrawal reflex is less detailed. There is, however, experimental evidence that the cerebellum is involved in performance of the limb withdrawal reflex. Early animal studies report changes of limb withdrawal reflex after lesions and stimulation of the cerebellum (Chambers and Sprague 1955; Denny-Brown et al. 1929) and inferior olive (Rabacchi et al. 1986). More recent studies describe limb withdrawal reflex changes after lesions of the paravermal cortex (Yu 1972) and interposed nuclei (Kolb et al. 1997). Although involvement of the intermediate cerebellum has been shown in limb withdrawal reflex control, no attempts have been made to map the cerebellar cortical lobules involved.

The number of human studies examining the cerebellar role in nociceptive limb withdrawal reflex control is more limited. Impaired leg withdrawal reflexes have been reported in patients with Friedreich’s ataxia (Shahani and Young 1971) and in a patient with a unilateral surgical cerebellar lesion (Timmann et al. 1998a). In a recent PET study by our group, changes of cerebellar activity evoked by nociceptive leg withdrawal reflex were observed within vermal regions primarily of the anterior lobe in healthy human subjects (Maschke et al. 2002a).

The aim of the present study was to use the high spatial and temporal resolution of event-related functional brain imaging (fMRI) to examine nociceptive leg withdrawal reflex–related cerebellar areas in humans. More detailed knowledge of un-
conditioned withdrawal reflex–related cerebellar areas are thought helpful to interpret data of limb withdrawal reflex conditioning studies both in cerebellar patients and in healthy human subjects using functional brain imaging.

METHODS

Subjects

Sixteen healthy adult subjects participated. Their average age was 30.8 ± 6.0 (range 22–41) years. Five subjects were female and 11 male. None of them had a history of neurological disease or revealed neurological signs based on neurological examination. All experiments were undertaken with the understanding and written consent of each subject. The local ethical committee of the University of Essen approved the study.

EMG recordings

Subjects were lying supine with the knee supported by a pillow and with their eyes closed. Nociceptive leg withdrawal reflexes were evoked by a train of bipolar current pulses (f = 100 Hz, pulse duration 0.65 ms) lasting for 100 ms applied through surface electrodes to the left tibial nerve behind the medial malleolus. The electrical stimulator (Elektrischer Stimulator ES, Jaeger Toennies, Hoechberg, Germany) was placed outside the MR scanning room. Before the recording session the sensory and motor thresholds were determined followed by successive increases of the current intensity until significant leg flexion responses were evoked. The mean sensory threshold was 1.2 mA (SD 0.5, range 0.4–1.5), mean motor threshold was 4.9 mA (SD 1.9, range 2–7), and mean leg withdrawal reflex stimulation strength was 14.3 mA (SD 7.5, range 6–30 mA).

An event-related fMRI paradigm (see following text) was applied with a total of 30 electrical stimuli being delivered pseudorandomly and with long intertrial intervals (range 28–56 s) during 500 consecutive MR scans. For each subject electrical stimuli were delivered at the end of MR scans 15, 35, 50, 67, 83, and 95, with the same order being repeated during the following 400 scans (115, 135, 150, 167, 183, 195, 215, 235, 250, etc.). Intervals of 600 ms were interposed between individual scans. Electrical stimulation occurred 186 ms after the beginning of the last of 22 slices of each scan and limb flexion reflexes were recorded within the interval without echo-planar imaging.

Electromyographic (EMG) activity was recorded from the left anterior tibial muscle (sampling rate 1,000 Hz). A pair of disposable surface carbon electrodes (ConMed), commonly used for ECG recording in the MR environment, was placed over the muscle belly. The overlying skin was cleaned with isopropyl alcohol (75%) and shaved if needed. A Velcro fastening ground strip was fixed between the site of stimulation and the recording site close to the ankle. The EMG signals were fed by carbon fiber cables (D120RL radiolucent cables, 3M Medica) to a battery-powered EMG amplifier (LWLEXX-amplifier, Institut für Explorative Datenanalyse, Hamburg, Germany) custom-built for use in the MR environment (gain: 50–100, filter: 10 (2 Hz < f < 2,000 Hz). Electrical signals were transformed into optical signals and transmitted by fiber-optic cables to a fiber-optic receiver placed outside the scanning room. EMG signals were fully rectified, further filtered (100 Hz), and stored for off-line analysis.

EMG analysis

The EMG data were analyzed on a trial-by-trial basis using commercial software (AxoGraph 3.5, Axon Instruments, Union City, CA). Visual inspection of each trial allowed identification of trials without significant flexion reflex activity. Further analysis of leg withdrawal reflex was limited because of superimposed artifacts. The nociceptive leg withdrawal reflex consists commonly of an early (F1) and a late (F2) reflex component that are separated by a silent period (S) (Meineck et al. 1983; Shahani and Young 1971). Because onset of the early F1 component frequently overlapped with the stimulation artifact, onset of the F2 component only was determined. Onset was defined where EMG activity significantly increased from baseline activity. The end of the reflex response was frequently difficult to determine largely because of cable movement artifacts. Data inspection revealed that a fixed interval of 50 ms was free of artifacts in most cases. Therefore integrated EMG (IEMG) was quantified for a fixed interval of 50 ms (50 ms-IEMG). Mean EMG baseline activity was acquired in a 100 ms-interval between electrical stimulation. Mean baseline activity was subtracted from 50 ms-IEMG. To allow for comparison between subjects, leg withdrawal reflex amplitudes were normalized to the mean amplitudes across all 30 trials in each individual subject. Each withdrawal reflex amplitude was expressed as a percentage of this value.

Means and SDs of F2 onsets and fixed 50 ms-IEMGs were calculated. To quantify possible changes across time (i.e., habituation and sensitization effects) linear regression analyses with 50 ms-IEMG as a dependent factor were performed across trials for the group of all subjects and each individual subject.

Imaging

All fMRI scans were taken with a 1.5 T Siemens Sonata scanner (Dept. of Neuroradiology, University of Essen, Germany) with standard head coil. A multislice echo planar imaging sequence (EPI) was used to produce 22 continuous 3-mm-thick axial slices covering the volume of the cerebellum and adjacent brain stem with TR = 2.8 s, TE = 60 ms, flip angle = 90°, 64 × 64 matrix and voxel size = 3.59 × 3.59 × 3 mm³. An event-related fMRI paradigm was used for the experiment. An electronic triggering signal was used to achieve synchronization between the time of initiation of the active event (electrical stimulus) and the MR acquisition. Each series consisted of 500 scans with a total duration of 23.3 min. Structural images were acquired for each subject using a T1 3D sequence with TR = 11.1 ms, TE = 4.3 ms, flip angle = 15°, 136 partitions, effective thickness = 1.2 mm, and voxel size = 1 × 1 × 1.2 mm³.

Image analysis

The stereotactical transformations and statistical analysis were carried out on a Sun Sparc Ultra 80 computer with statistical parametric mapping software (version SPM99; Wellcome Department of Cognitive Neurology, London, UK), implemented in MATLAB (Mathworks, Sherborn, MA). The functional images were first subjected to a slice time–alignment process. This correction procedure is necessary to minimize image intensity inhomogeneity arising from differences in slice image acquisition timing. All individual volumes were re-aligned after the 6 head-movement parameters were estimated (3 translations and 3 rotations) from rigid body transformations. The realignment procedure minimizes the displacement effects between each volume of the time series and the first. Images were then spatially normalized (Friston et al. 1995) into the reference system of Talairach and Tournoux (1988), using a representative standard EPI template from the Montreal Neurological Institute (MNI; Evans et al. 1994). The functional images were subsampled to a voxel size of 2 × 2 × 2 mm³ and smoothed using an isotropic Gaussian kernel of 6 mm.

The statistical analysis was performed for each time series after specifying the appropriate design matrix. The active event was modeled with hemodynamic response functions (HRF). The 6 head-movement parameters were included as trial-specific covariates in the design matrix to take into account effects of head movement–related changes after electrical stimulation of the foot. To minimize the effects of magnetization relaxation artifacts and to reduce the effects of accompanying startlelike reactions (see Results, Nociceptive withdrawal reflex recordings), scans corresponding to the first two stimuli
(i.e., the first 40 scans of each time series) were excluded from statistical analysis.

The significance of effects was assessed using Z statistics for every voxel from the brain, and these sets of Z values were used to create statistical parametric maps (SPMs). A high-pass filter was used to remove low-frequency drifts and fluctuations of the signal (Friston et al. 1996), and proportional scaling was applied to remove global changes in the signal.

Data were analyzed for each subject individually and for subjects as a group. Group effects were calculated using random effects models. Contrast images, one for each single subject, were taken to the second-level analysis and entered into the one-sample t-test model (Friston et al. 1999). The statistical test of variance of these single contrast images from subject to subject consists of contributions from both the between- and within-subject components of variance and can be used to extend the inference to population.

The specified contrasts compared the active event condition with rest. Only trials with significant EMG activity were used as active events in fMRI statistical analysis (see RESULTS, Nociceptive withdrawal reflex recordings). In 3 subjects no significant flexion reflexes were observed in EMG recordings. Data from these 3 subjects were excluded from statistical analysis. For the group study a threshold of $P < 0.0001$ (uncorrected; extended threshold 20 voxels) was adopted. Thresholds for statistical analysis of individual subjects were set as $P < 0.001$ (uncorrected; extended threshold 20 voxels). Anatomical localization of MNI coordinates were defined based on the 3D MRI atlas of the human cerebellum in proportional stereotaxical space developed by Schmahmann et al. (2000) and the 3D MRI atlas of the human cerebellar nuclei developed by Dimitrova et al. (2002b). The lateral extent of the vermis is difficult to define, particularly within the anterior lobe (Schmahmann et al. 2000). As an approximation, vermal activation was defined as activation within an x-range of $-10 \, \text{mm}$ and 10 mm. Activation more laterally than 10 mm from the AC-PC line was defined as activation within the cerebellar hemispheres.

For localization of cerebral activation the Talairach and Tournoux atlas (1988) was used. To correct for a certain mismatch between MNI and Talairach and Tournoux space, MNI coordinates were transferred to the Talairach and Tournoux space using the algorithms described in http://www.mrc-cbu.cam.ac.uk/Imaging/mnispace.html.

**RESULTS**

**Nociceptive withdrawal reflex recordings**

Visual inspection of surface EMG recordings of the anterior tibial muscle revealed that leg withdrawal responses were present on average in 84% (SD 21%; range 50–100%) of the trials in 13 of the 16 subjects. In 3 subjects no significant limb flexion response activity was observed; these 3 subjects were excluded from fMRI analysis. Onsets and 50 ms-IEMGs of the flexion response were determined in 9 of the 13 subjects with provable withdrawal responses. In the remaining 4 subjects prominent artifacts prevented more detailed EMG analysis.

Individual, nonrectified EMG recordings of one subject (s-9 in Tables 1 and 2) are shown in Fig. 1A. The beginning of electrical stimulation within the MR scanning-free interval is indicated by a vertical line. The electrical stimulation is followed by EMG bursts in all 30 trials, with the first trial at the top and the last trial at the bottom. The beginning of subsequent MR scanning is indicated by the artifacts at the end of each trace. EMG responses were largest within the initial trials with no prominent change of response size in the remaining trials.

Mean changes of response size (normalized 50 ms-IEMG) across trials in the group of all subjects are shown in Fig. 1B.
borders between fastigial and interposed nuclei are difficult to define, activation of parts of the interposed nuclei cannot be excluded.

The second largest cluster of activation (cluster size = 121) was present in paravermis of the left anterior lobe with an absolute maximum in paravermal lobule IV (−22, −32, −36; Z = 4.85) and an additional maximum in lobule VI (−30, −44, −34; Z = 4.71). The third largest cluster (cluster size = 77) was located within left Crus I (−42, −64, −32; Z = 4.89). Smaller clusters of activations were present within right paravermal lobules III/IV (24, −34, −34; Z = 4.63), and hemispheral lobules V (28, −38, −28; Z = 4.12) and VI (28, −48, −32; Z = 4.87). In addition, small clusters of activation were located within left paravermal lobule VIII A (−22, −72, −52; Z = 4.78) and right paravermal lobule VIIIB (24, −44, −56; Z = 4.67). On the group level, no significant extracerebellar activations (e.g., within the temporal lobes or brain stem) were found. The statistical group data from the random model are displayed on axial sections of a typical canonical MNI brain in Fig. 4. Table 1 summarizes the Z-scores and MNI coordinates for the vermal activation for the random model group analysis as well as for each single subject. Table 2 summarizes the data for the hemispheral activation.

Analysis in individual subjects showed a similar pattern of activation within the vermis and cerebellar hemispheres. In 6 subjects (s-1–s-6) withdrawal reflex–related activation was present in vermal lobule III and/or IV. In 2 subjects vermal activation was present in lobules I/II (s-5, s-7). Vermal activation in the 7 subjects is displayed on sagittal sections of the individual normalized anatomical data sets in Fig. 5. Activation in vermal lobule VI was present in 9 subjects with additional activation in vermal lobule V in 2 subjects. Vermal activation in lobule VI is shown in 6 individual subjects in Fig. 5 (s-1, s-2, s-3, s-5, s-7, and s-10). Note that in s-2 the nearest local

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**fig. 2.** Group data (n = 13) shown based on random effects model (P < 0.0001, uncorrected). SPM (t) maps displayed in sagittal, coronal, and axial projections. Volume scanned covered entire cerebellum and parts of adjacent occipital, temporal, and frontal lobes. Laterality is indicated by L (left) and R (right).

2 trials, however, were excluded from fMRI analysis to reduce effects of startlelike responses.

In the group of all subjects, the mean onset of leg withdrawal response (i.e., the F2 component) was 160 ms (SD 47 ms). Latencies were within the range described in the literature for nociceptive leg withdrawal reflex recordings without preinnervation of the anterior tibial muscle (e.g., Shahani and Young 1971; Torring et al. 1981).

**fMRI data**

SPM (t) maps of random model group analysis (P < 0.0001, uncorrected) are shown in Fig. 2. Nociceptive leg withdrawal reflex–related areas of cerebellar activations were present within the vermis, paravermal areas, and the lateral posterior hemispheres. Local maxima were found within the anterior vermis (lobules III/IV) and the posterior vermis (lobules VI and VIII). Activation extended into the fastigial nuclei. Paravermal areas were activated bilaterally within the anterior lobe (lobules III/IV) and posterior lobe (lobule VIII). Within the lateral posterior hemispheres local maxima were found within lobules VI and Crus I on the left and lobules V and VI on the right. Hemispheral activations were more prominent on the left.

Group analysis revealed the largest cluster of activation (cluster size = 308) within the vermis with an absolute maximum in lobule VI [x, y, z coordinates in mm (−2, −64, −26; Z = 4.96)] extending into lobule V (−2, −64, −12; Z = 4.55). Additional local maxima were present within lobule III (−6, −44, −20; Z = 4.15), extending into lobule IV (−4, −48, −16; Z = 4.17), and lobule VIII A (−2, −68, −42; Z = 4.75; −2, −66, −34; Z = 4.58), extending into lobule VIII B (−2, −58, −30; Z = 4.77). Figure 3 illustrates that the cluster of activation included the fastigial nuclei. The statistical group data from the random model are displayed on MR templates taken from the 3D atlas of the human cerebellum nuclei developed by our group (Dimitrova et al. 2000b). An area of significant activation is seen in the roof of the fourth ventricle (2, −52, −28), which is consistent with the known location of the fastigial nuclei (Angevine et al. 1961; Duvernoy 1995). There was no significant activation of the interposed and dentate nuclei (I and D in Fig. 3). However, because the exact

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**fig. 3.** SPM (t) maps of group data (random effects model; P < 0.0001, uncorrected) displayed on sagittal, coronal, and axial sections of template from the 3D MRI atlas of human cerebellum nuclei (Dimitrova et al. 2002b). Note activation in roof of fourth ventricle, i.e., the location of the fastigial nuclei. I, interposed nucleus; D, dentate nucleus.
maximum was within vermal lobule VIIA and activation in VI is therefore not listed in Table 1. Vermal lobule VIIA was activated in 5 subjects, with extension into lobule VIIIIB in one subject. Vermal lobule VII was activated in 7 subjects. Activation of vermal lobules VII and/or VIII is shown in 7 of these subjects (s-1–s-7) in Fig. 5. Vermal activation extended into the region of the fastigial nuclei in 6 subjects. Activation overlapped with MNI coordinates of fastigial nuclei based on Dimitrova et al. (2002b) in 3 subjects (s-1, s-6, s-8 in Table 1) and was in close proximity in the other 3 subjects (s-2, s-3, s-7). Activation extending into the roof of the fourth ventricle is seen in 4 of the individual subjects in Fig. 5 (s-1, s-2, s-3, s-7). Activation overlapping with the location of the dentate or interposed nuclei was present in 5 subjects [s-2: right interposed (4, −68, −38; Z = 4.46); s-3: left interposed (−14, −56, −26; Z = 4.8); s-4: left dentate (−18, −66, −38; Z = 5.34); s-7: left dentate (−14, −58, −36; Z = 3.86); s-8: left interposed (−8, 52, −24; Z = 4.72)].

Activation of paravermal lobules III/IV was present in one subject on the left, in 5 subjects bilaterally, and in 3 subjects on the right. Activation of paravermal lobules VIIIAB was present in 4 subjects on the left, in 4 subjects bilaterally, and in one subject on the right. Two subjects showed activation in left lobule VII. Finally, activation of hemispheral lobule VI was present in 5 subjects on the left and in 4 subjects bilaterally. Activation of lobule Crus I was present in 3 subjects on the left, in 2 subjects bilaterally, and in 4 subjects on the right.

In 10 individual subjects additional activation was found within the temporal lobes. Temporal activation was on the left in 3 subjects and bilateral in 7 subjects. The location of activation within the temporal lobes varied between individual subjects. Locations included gyrus temporalis superior and medius, gyrus parahippocampalis, uncus, and amygdala.

**Discussion**

Different areas within the cerebellum showed a significant change of activity related to the nociceptive leg withdrawal response. The results showed increased activity in the vermis, paravermian, and hemispheric lobules. The vermal lobules VII and VIII were activated bilaterally in most of the subjects. The paravermian lobules III/IV and VIIIAB were activated in 4 and 5 subjects, respectively. The hemispheral lobules VI and Crus I were activated in 5 and 3 subjects, respectively.

The coordinates of activation were consistent with the known anatomy of the cerebellum, with the vermal lobules showing the most significant activity. The paravermian and hemispheral lobules also showed activation, indicating that activation extends beyond the vermis into these regions. The results suggest that the cerebellum plays a role in the processing of nociceptive information, with the vermis being the primary region of activation.

**Table 1. Coordinates in MNI standard anatomical space for the peaks (i.e., local maxima) of cerebellar vermal activation**

<table>
<thead>
<tr>
<th>Group</th>
<th>Subject</th>
<th>x, y, z</th>
<th>Z</th>
<th>lob.</th>
<th>x, y, z</th>
<th>Z</th>
<th>lob.</th>
<th>x, y, z</th>
<th>Z</th>
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<tbody>
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<td>−6, −44, −20</td>
<td>4.15</td>
<td>III</td>
<td>−2, −64, −26</td>
<td>4.96</td>
<td>VI</td>
<td>−2, −68, −42</td>
<td>4.75</td>
<td>VIIA</td>
</tr>
<tr>
<td>s-2</td>
<td>−4, −48, −16</td>
<td>4.17</td>
<td>III/IV</td>
<td>−2, −64, −12</td>
<td>4.55</td>
<td>V</td>
<td>−2, −58, −30</td>
<td>4.77</td>
<td>VIIIB</td>
</tr>
<tr>
<td>s-3</td>
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<td>&gt;7.77</td>
<td>IV</td>
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<td>5.86</td>
<td>VI</td>
<td>−10, −72, −48</td>
<td>5.78</td>
<td>VIIA</td>
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<td>5.95</td>
<td>III</td>
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<td>VI</td>
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<td>5.20</td>
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<td>7.40</td>
<td>VI</td>
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<td>VIIB/VIIA</td>
</tr>
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<td>V</td>
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Error probabilities for group analysis (random model): $P < 0.0001$ (uncorrected); for individual subjects: $P < 0.001$ (uncorrected). x, y, z, coordinates in mm; Z, Z-score; lob., lobule; † activation overlap with fastigial coordinates; * activation in close neighborhood of fastigial coordinates (based on Dimitrova et al. 2002b). Note that coordinates of fastigial activation correspond to the nearest local maximum of the cluster and may differ from localization of fastigial nuclei.

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TABLE 2. Coordinates in MNI standard anatomical space for the peaks (i.e., local maxima) of cerebellar hemispheral activation

<table>
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<th>Right Cerebellar Hemisphere</th>
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<tr>
<td>Subject</td>
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<td>III/IV</td>
<td>VI/Crus I</td>
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</tr>
<tr>
<td>s-2</td>
<td>$-30$, $-44$, $-34$</td>
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<tr>
<td>s-13</td>
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</table>

Error probabilities for group analysis (random model): $P < 0.0001$ (uncorrected); for individual subjects: $P < 0.001$ (uncorrected). $x$, $y$, $z$, coordinates in mm; Z, Z-score; lob., lobule; Cr. 1, Crus I.

reflex. Areas were located within anterior and posterior parts of the vermis and paravermis as well as both posterior lateral cerebellar hemispheres. Vermal and paravermal areas (i.e., lobules III and IV in the anterior lobe and lobule VIII in the posterior lobe) match with areas known to be involved in leg control and are likely related to the withdrawal of the limb from the noxious stimulus (Hagbarth and Finer 1963; Kugelberg et al. 1960; Sherrington 1910). The other areas within the posterior lobe (i.e., hemispheral lobules VI and Crus I, vermal lobule VI) may be related to other pain-related processes (e.g., pain-induced facial grimacing and/or fear; Craig 1984) and startlelike reactions (Bromm and Scharein 1982; Dowman 1992).

Findings confirm and extend results of our previous PET study of the nociceptive leg withdrawal response (Maschke et al. 2002a). Activations of the anterior vermis and more anterior parts of the posterior vermis (i.e., vermal lobules III–VI) were present in both studies. In the present fMRI study additional activations were observed in the posterior vermis and posterior cerebellar hemispheres. The more widespread cerebellar activation are likely a consequence of the better temporal and spatial resolution of event-related fMRI compared with PET.

Cerebellar activation related to the spinal nociceptive leg withdrawal reflex

Nociceptive leg withdrawal reflex–related areas within the vermal and paravermal areas of the anterior lobe (i.e., lobules III/IV) and the more posterior parts of the posterior lobe (i.e., lobule VIII) agree with the known cerebellar representation of the hindlimb and leg. Somatotopic representation in the cerebellum with two homunculi, one located upside down in the anterior lobe and a second one in the posterior lobe, was first described by Adrian (1943) and Snider and Stowell (1944). Although subsequent anatomical and electrophysiological studies have revealed a more complex spatial distribution of mossy and climbing fiber afferents, a rough somatotopical pattern appears to be present (Brodal 1975; Ekerot et al. 1991a,b; Oscarsson 1976; Welker 1987; for reviews see Bodel and Courville 1974; Voogd and Glickstein 1998). Consistent with the present findings, climbing fiber hindlimb afferents have been found to the more rostral vermal and paravermal parts of the anterior lobe (Garwicz 1997) and to the more

FIG. 5. Data of eight single subjects shown. SPM (t) maps ($P < 0.001$, uncorrected) displayed on sagittal sections of individual normalized T1-weighted MR data sets.
posterior vermal parts of the posterior lobe (i.e., vermal lobule VIII) (Atkins and Apps 1997).

More recent fMRI studies have confirmed the existence of a similar somatotopic representation in humans. In agreement with the present findings, representation of foot movements has been found both within the more anterior parts of the anterior lobe (i.e., in hemispheral lobules II–IV with extension into the vermis; Grodd et al. 2001; Nitschke et al. 1996; Rijntjes et al. 1999) and within the more posterior parts of the paravermal hemispheres (hemispheral lobules VII–VIII; Rijntjes et al. 1999) and vermis of the posterior lobe (Grodd et al. 2001; Rijntjes et al. 1999).

Paravermal activation was present bilaterally. Contralateral cerebellar activation may reflect movement of the contralateral limb and/or bilateral representation of sensory afferents. Electrical stimulation of one limb results in withdrawal of the stimulated limb and concomitant postural adjustments of the contralateral limb (e.g., extension during standing) (Hagbarth and Finer 1963; Kugelberg 1960; Sherrington 1910). In addition, cerebellar afferents have been shown to have a large ipsilateral and a smaller contralateral cerebellar representation (Bloedel and Courville 1974; Brodal 1981).

No voluntary foot movement and pure sensory stimulation conditions were performed in the present study. Therefore the present study does not allow differentiation if the reflex-related cerebellar activity reflects cerebellar modulation of the spinal reflex pathways, afferent input of the noxious stimulus, and/or afferent feedback of the limb withdrawal. It appears, however, likely that the afferent input is used to modulate the spinal nociceptive leg withdrawal reflex. As outlined in the introduction changes of reflex amplitude have been found in a human case study (Timmann et al. 1998a) and animal lesion studies of the cerebellum (Chambers and Sprague 1955; Denny-Brown et al. 1929; Kolb et al. 1997; Yu 1972) and inferior olive (Rabacchi et al. 1986).

Findings of animal lesion studies, however, are not unequivocal. Despite clear deficits of classical conditioning, others have found no changes of the unconditioned limb withdrawal reflex after lesions of the interposed nucleus (Donegan et al. 1983), brachium conjunctivum (Voneida 2000), red nucleus (Smith 1970; Tsukahara et al. 1981), rubrospinal tract (Voneida 1999), and inferior olive (Voneida et al. 1990). Electrophysiological animal studies, on the other hand, provide detailed evidence that the spino-olivo-cerebellar system is involved in nociceptive limb withdrawal reflex control (Ekerot et al. 1991a,b; Garwitz et al. 1992, 2002; Kalliomäki et al. 1992; Oscarsson 1973; Schouenborg and Weng 1994; Schouenborg et al. 1994). The organization of cutaneous receptive fibers for spino-olivo-cerebellar pathways to cerebellar zones controlling detailed limb movements has been shown to resemble that of the nociceptive withdrawal reflexes (Ekerot et al. 1991a,b; Garwicz et al. 1992). Partial overlap of cerebellar areas activated during limb flexion reflex in the present fMRI study and during voluntary leg movements in previous fMRI studies is consistent with this finding. Overlap of cerebellar areas during voluntary and reflexive leg movement is further supported by the recent PET study of our group. Limb flexion reflex-related areas were found within the upper vermis of the anterior lobe including lobules III and IV. These areas partially overlapped with vermal activation areas in a voluntary foot movement condition (Maschke et al. 2002a). Similar cerebellar areas may be involved in control of reflexive and voluntary limb movements by modulating spinal neuronal networks that implement the withdrawal reflexes and also mediate signals from supraspinal motor centers involved in coordination of voluntary motor behavior (Jankowska 1992; Kalliomäki et al. 1992; Kolb et al. 1997; Lundberg 1982; Schomburg 1990; Schouenborg and Weng 1994). Future studies need to investigate possible impairment of performance of the nociceptive leg withdrawal reflex in a larger group of cerebellar patients.

Cerebellar activation related to other pain-related reactions

In addition to areas that overlap with the known cerebellar representation of the leg, nociceptive leg withdrawal-related activation was present within the anterior parts of the posterior vermis (lobule VI), with extension into lobule V and the fastigial nuclei and the anterior parts of the posterior cerebellar hemispheres bilaterally (lobules VI/Crus I). Consistent with the present findings, withdrawal reflex-related activity extended into vermal lobules V and VI in our recent PET study (Maschke et al. 2002a). These areas may be related to functions other than the reflexive withdrawal of the leg. Electrical stimulation is accompanied by sensation of pain, facial expressions of pain, fear, and startlelike reactions (Craig 1984; Craig and Patrick 1985; Downman 1992; Ploghaus et al. 1999). There is evidence from the animal and functional human brain imaging literature that the cerebellum may be involved in these pain-induced reactions.

First, painful stimuli are accompanied by facial actions including eye closing or blinking (Craig and Patrick 1985). Cerebellar somatotopic representation of facial afferents and movements is known to be within the posterior cerebellar lobe (i.e., vermal and paravermal lobules VI and VII) (Grodd et al. 2001; Hessler 1994a,b; Nitschke et al. 1996; Snider and Stowell 1944). Likewise, a recent fMRI study of our group showed blink reflex-related areas within bilateral hemispheral lobules VI and Crus I with extension into the vermis (Dimitrova et al. 2002a). Reflex eyeblinking as part of startlelike responses may also account for at least part of activation in areas representing facial movements. Responses to the first two stimuli were excluded from analysis to minimize the effects of startlelike reactions. Whole body startle habituates within few trials. Startle-related eyeblinks, however, take a slower course of habituation and their occurrence cannot be excluded in later trials (Koch 1999; Maschke et al. 2000). Furthermore, the cerebellar vermis, particularly lobule VI, and adjacent parts of the hemispheres have been shown to be involved in modulation of the startle reflex (i.e., habituation and fear-induced potentiation) (Frings et al. 2002; Leaton and Supple 1991; Lopiano et al. 1990; Pissioti et al. 2002; Timmann et al. 1998b).

Thus cerebellar activation of the anterior part of the posterior cerebellum may reflect pain-induced facial movements (e.g., grimacing and/or startle-related eyeblinking). An increasing number of studies, however, suggest that the cerebellum is involved in nonmotor functions including affect and behavior (see Schmahmann 1997 for review). Areas within the neocerebellum, for example, the neovermis (i.e., lobules VI/VII) and the posterior cerebellar hemispheres (i.e., lobule VI and below), appear to be of particular importance (Akshoomoff and Courchesne 1994; Schmahmann and Sherman 1998; Thach 1998).
Likewise, cerebellar activation of the vermis and posterior cerebellar hemispheres have been demonstrated in fMRI studies of neural substrates involved in pain (Becerra et al. 1999; Coghill et al. 1999; Svensson et al. 1997). On the basis of Schmahmann et al.’s (2000) atlas of the human cerebellum, activations were found primarily within lobule VI. Ploghaus et al. (1999) showed that different areas in the cerebellum are involved in different aspects of pain processing. In their study, painful stimuli of the hand evoked responses of the anterior cerebellum (i.e., within the known hand areal), whereas expectation of the same stimuli evoked activations within the posterior cerebellar hemisphere. Vermal and paravermal areas of the anterior lobe and more posterior parts of the posterior lobe (corresponding to the somatotopic representation of the stimulated limb) may be involved with integration of nociceptive information to other motor areas, whereas neocerebellar areas within the posterior hemispheres may be involved in other (e.g., affective or cognitive) dimensions of pain.

Finally, pain is frequently accompanied by fear. Both the cerebellar vermis and the posterior cerebellar hemispheres have been shown to be activated as a result of externally evoked emotions (Beauregard et al. 1998; Lane et al. 1997; Reiman et al. 1997). In most fMRI studies areas of activation were located within vermal lobules V/VI and in hemispherical lobules VI/Crus I (based on Schmahmann et al.’s atlas).

Cerebellar activations attributed to pain-related reactions other than the actual limb withdrawal are further supported by the likely activation of the fastigial nuclei. Fear is known to be accompanied by changes of autonomic functions (for review see Schmahmann 2000). Within the posterior lateral hemispheres may be involved in other (e.g., affective or cognitive) dimensions of pain.

Hemispherical activations on the group level were more prominent on the left. Although this may simply reflect effects of stimulation side, another explanation appears worth mentioning. The oldest model of emotion lateralization holds that the right cerebral hemisphere is dominant for emotional processing. An alternative view posits that the left cerebral hemisphere is preferentially involved in positive emotions and approach, whereas the right hemisphere is preferentially involved in negative emotions and withdrawal (Zald 2003). These models focus on the prefrontal cortex. Because of the known connections of the left cerebellum to the right prefrontal cortex (Middleton and Strick 1994), fear-related activation of the cerebellum may be expected on the left.

In conclusion, in addition to actual limb withdrawal, a variety of other motor and nonmotor reactions are induced by pain that appear able to induce changes of cerebellar activity in the posterior cerebellar lobe. Quantitative assessment of facial movements, startlelike reactions, and fear-induced autonomic changes (i.e., skin conductance response, heart rate) may be helpful to differentiate between the possibilities in future studies.

Different areas within the vermis and cerebellar hemispheres appear to be related to the nociceptive leg withdrawal reflex. Vermal and paravermal areas overlapping with the known representation of the leg are likely related to the leg withdrawal reflex in itself. Areas within the posterior lateral hemispheres and neovermis appear to be related to other pain-induced reactions. Studies of conditioning of the nociceptive limb withdrawal reflex should take these findings into consideration. Conditioning of the electrically evoked leg withdrawal reflex will induce conditioning of specific (i.e., the leg withdrawal) and nonspecific (e.g., fear, changes of heart rate) aversive reactions (Lavond et al. 1993). Accordingly, in fMRI studies in healthy human subjects different cerebellar areas are likely to be activated. Likewise, in patients with focal cerebellar lesions concomitant conditioning of specific and nonspecific aversive reactions is likely to be differentially affected depending on the side of the lesion.

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