Cerebellar Engagement in an Action Observation Network

The cerebellum has traditionally been viewed as a brain structure suberving skilled motor behaviors. However, the cerebellum might be involved not only in movement coordination, but also in action observation and understanding of others’ actions. Veridical visual perception of human body motion is of immense importance for a variety of daily-life situations and for successful social interactions. While, by combining visual psychophysics with a lesion analysis, we assessed visual sensitivity to human walking in patients with lesions to the left cerebellum. Patients with left lateral cerebellar lesions exhibit deficits in visual sensitivity to body motion, whereas medial lesions do not substantially affect visual perception of human locomotion. The findings point to the role of the cerebellum in action observation network. We discuss possible mechanisms of cerebellar engagement in visual social perception revealed by body motion.

Keywords: biological motion, cerebellum, lesions, visual psychophysics

Introduction

The cerebellum has traditionally been viewed as a brain structure suberving skilled motor behaviors, and cerebellar damage is commonly associated with difficulties in motor control and posture balance. Recent work suggests a much broader functional value of the cerebellum with contributions to a number of higher cognitive functions ranging from working memory and visual attention to social skills (Middleton and Strick 1994; Ackermann et al. 2007; Stoodley and Schmahmann 2009). However, the findings are controversial (Glickstein 2006; Haarmeier and Thier 2007). Brain imaging in humans as well as nonprimate lesion data suggest that the cerebellum might be involved not only in movement coordination, but also in visual action observation (Leggio et al. 2000; Gallagher and Frith 2004; Calvo-Merino et al. 2006; Frey and Gerry 2006; Gazzola and Keysers 2009).

Veridical visual perception of others’ actions is of immense value for a variety of daily-life situations, such as safe car driving and self-locomotion, as well as for successful social communication (Puce and Perrett 2003; De Gelder 2006; Blake and Shiffrar 2007). Body movements help to improve our social interaction by means of nonverbal information about social properties such as intentions, emotions and dispositions of others. Visual sensitivity to body motion emerges early in perceptual development (Fox and McDaniel 1982), and is well preserved in the elderly (Norman et al. 2004). Moreover, preference for biological motion is believed to be predisposed in the brain of vertebrates (Vallortigara et al. 2005). Brain imaging in humans, single cell recording in the macaque monkey, and neuropsychological lesion studies suggest that body motion processing engages a specialized neural network that differs from processing of other moving stimuli (Grossman et al. 2000; Vaina et al. 2001; Grossman and Blake 2002; Pelphrey et al. 2003; Jellema et al. 2004; Pavlova et al. 2004; Peelen et al. 2006; Saygin 2007). Proper functioning of this network depends on intact communication between several areas throughout the brain. Early periventricular lesions that impair brain connectivity lead to reduced visual sensitivity and affect cortical neuromagnetic response to body movements (Pavlova et al. 2003, 2005, 2007, 2009). Brain imaging reveals that the posterior temporal cortex, in particular, the superior temporal sulcus (STS) and parietal regions in the right cerebral hemisphere are an essential part of the brain network engaged in visual processing of body motion (Bonda et al. 1996; Grossman et al. 2000; Beauchamp et al. 2005; Pelphrey et al. 2003, 2005; Zacks et al. 2006).

According to neuroanatomical findings in monkey and humans, the cerebellum might have contralateral interconnections primarily via the thalamus and also the basis pontis with multiple cortical areas in both cerebral hemispheres (Middleton and Strick 1994; Hoschi et al. 2005), including the posterior areas of the parieto-temporal cortex (Dum and Strick 2003; Clower et al. 2005) and the STS (Schmahmann and Pandya 1991; Booth et al. 2007). Multiple loops operate both in feedback (cerebral cortex to the cerebellum) and feedback directions (Middleton and Strick 1994). Whereas the vermis of the cerebellum (in particular, its lower lobes) represents the cerebellar limbic system involved in modulation of emotions and social behavior, more lateral regions are believed to engage in modulation of higher cognitive functions (Schmahmann et al. 2007). The intracerebellar functional differentiation appears to emerge already in childhood. Children with right cerebellar damage exhibit impairments of language processing, whereas left hemispheric lesions result in visual spatial deficits (Riva and Giorgi 2000; Scott et al. 2001). Because of contralateral connections, the left cerebellum may interact with the right temporal cortex that is heavily involved in visual processing of body motion (Bonda et al. 1996; Grossman et al. 2000; Beauchamp et al. 2003; Pelphrey et al. 2003, 2005; Zacks et al. 2006). For this reason, we assume that the left cerebellar hemisphere might be important for visual processing of human locomotion.

Although in healthy adults functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) reveal cerebellar activation during visual perception of human walking (Grossman et al. 2000; Vaina et al. 2001; Piito et al. 2003), there is a lack of consensus as to cerebellar substruc-
cerebellar lesions of different topography affect visual processing of human locomotion. Convergent evidence from neuroimaging and lesion studies is of importance for establishing structure-function relationships. Methodological difficulties, however, can lead to a failure in attempts to reveal deficits in visual processing of body motion in patients with heterogeneous lesion topography (Jokisch et al. 2005). Here we address the issue of whether and, if so, how damage to the cerebellum affects visual perception of body motion in patients with medial and lateral left cerebellar lesions selected for similar lesion extent and topography. Taking advantage of point-light methodology that isolates information about body motion from featural cues, and, therefore, minimizes the availability of structural information, we had patients with cerebellar lesions and matched healthy controls detect a point-light walking figure consisting of a number of dots placed on the main joints of an otherwise invisible human body (Fig. 1A).

**Methods**

**Participants**

Eleven patients (aged 26–51 years) with tumors to the left cerebellum participated in the psychophysical part of the study. One patient had a lesion of large extent affecting both medial and lateral cerebellum, and 2 patients declined to properly complete psychophysical testing. After lesion analysis (see below), 2 groups of patients with similar lesion topography entered subsequent data processing: 4 patients with left medial (1 female, 3 male, mean age 41.1 ± 3.5 years), and 4 patients with left lateral (3 female, 1 male, 37.5 ± 10.8 years) cerebellar tumors revealed on a structural MRI scan. Medial cerebellar lesions were located closely to cerebellar midline, whereas lateral cerebellar lesions were confined to the left lateral cerebellar hemisphere (Fig. 2). No other signs of brain abnormality were detectable on an MRI scan. Medial cerebellar lesions were confined to the left lateral cerebellar hemisphere (Fig. 2). No other signs of brain abnormality were detectable on an MRI scan. Neither radiological nor neurological signs of increased intracranial pressure were observed. There were no age differences between the patient groups (Mann-Whitney test, U = 11, n.s.). Healthy participants person-to-person matched for age, gender, socioeconomic, and educational status to each cerebellar patient were recruited from the local community. None of the controls had a history of neurological or psychiatric disorders. All participants were right-handed and had normal or corrected-to-normal vision. They had normal verbal IQ (Wechsler-Intelligenztest für Erwachsene, a battery based on the Wechsler Adult Intelligence Scale (WAIS-III) by David Wechsler adapted to the German population, Von Aster et al. 2006). Tumors varied in their etiology, including hemangioblastoma, low grade glioma, medulloblastoma, and glioblastoma, with equal representation of benign and malignant entity in both groups. Psychophysical examination was conducted before neurosurgery. Patients did not have radio- or chemotherapy prior to and at time of testing. Neurological and ophthalmological examination did not reveal any oculomotor deficits. Patients with left lateral cerebellar lesions were free from fine motor, posture or balance deficits. One patient with medial cerebellar lesion exhibited an uncertain gait pattern, another patient had discrete left hypacusis and fine motor deficits (dyssyndochokinesia) in the left hand. In one medial cerebellar patient, a dysmetria of the left hand was observed. No other neurological deficits were found.

**Lesion Analysis**

Cerebellar lesions were identified by structural whole-brain MRI recording performed on a 1.5-T scanner (Siemens Medical Solutions, Erlangen, Germany). MRI scans included $T_1$, $T_2$, FLAIR, and diffusion weighted sequences. By using MRICro software (http://www.sph.sc.edu/comd/orden/mricro.html), the lesions were manually traced on each slice of $T_1$-weighted sequences (32 axial slices, TR [repetition time] 500 ms, TE [echo time] 12 ms, 4-mm slice thickness). Image alignment to stereotaxic space allowed one to compare lesion topography and extent between the patients, and to relate lesion topography to activation in functional imaging studies showing cerebellar involvement in visual processing of body motion (Grèzes et al. 2004, 2007). Before spatial normalization of the $T_1$ images by Statistical Parametric Mapping 2 (SPM2, Wellcome Institute of Cognitive Neuroscience, London, UK, http://www.fil.ion.ucl.ac.uk/spm/software/spm2), the lesions were masked in order to avoid disruption of automated SPM2 normalization functions and undue distortion of the images (Brett et al. 2001). Prior to normalization, the source images were manually reoriented so that their origin and rotation matched those of the $T_2$ $T_1$-template. To ensure that only voxels located within the brain were included in the normalization process, the SPM2 threshold template brain mask was used. The images were then automatically aligned to the $T_1$-template by using linear transformations. Finally, nonlinear cosine transformations were performed for matching of image details. Lesion volumetry was conducted by MRICro on normalized images. For patients with medial cerebellar lesions, the resulting lesion volume was 16.78 ± 8.43 mL. For patients with lateral lesions, it was 20.1 ± 11.48 mL. There was no difference in volumetric lesion extent between the groups (Mann-Whitney test, $U$ = 7.5, n.s.). According to the 3D-MRI atlas of the human cerebellum in proportional stereotaxic space (Schmahmann et al. 1999), the lobules I, II, III, IV, and V were affected in patients with medial lesions. In patients with lateral lesions, lesions were located in the lobules VIb, VIIa, Crus I, and Crus II. For lateral and medial cerebellar lesions, separate density plots were created by using the MRICro intersection method. These plots represent regions of mutual involvement of either lateral or medial cerebellar lesions. Figure 2 shows the resulting axial, coronal, and sagittal density plots displayed on a $T_1$-weighted MRI image in stereotaxic space provided with the MRICro package. This $T_1$-weighted image is an average of 27 scans of the same subject (http://www.bic.mni.mcgill.ca/cgi/ichm_view).

**Figure 1.** Upright (A) and inverted 180° mirror-image, (B) point-light walking figures simultaneously camouflaged by a 44-dot moving mask. For illustrative purposes, an outline of the walking figure is presented. Participants saw only a set of 55 bright dots either in walker-present or in walker-absent (mask only) displays. The motion of each dot of the mask was identical to the motion of one of the dots defining the point-light figure. The type, size, luminance, and phase relations of the dots also remained unchanged.
Cerebellum and Visual Perception of Body Movement

A point-light walker was comprised of 11 dots placed on the joints (ankles, shoulder, etc.) of an otherwise invisible human body. It was seen moving and facing right, in a sagittal view, with no net translation. A gait cycle was accomplished in 40 frames with frame duration of 36 ms. One type of stimulus represented a point-light walker embedded in an array of 44 distracters competing with motions of the walker’s dots (Fig. 1.4). Each of 4 sets of distracters consisted of 11 spatially scrambled dots on the joints of a point-light walker. The motion of each dot of the set was identical to the motion of one of the dots defining the canonical point-light figure. The other type of stimulus was a 55-dot mask: additional 11 dots were added to the walker-absent displays so that their density matched that of the walker-present displays. The type, size, luminance, and phase relations of the dots were the same in walker-present and walker-absent displays. At a viewing distance of 57 cm, the walking figure subtended a visual angle of 4.0° in height and 2.8° in width at the most extended point of a gait cycle. In a display, masking dots were randomly distributed in space within a region of about 5° in height by 7° in width. Head movements were restricted by the head-and-chin rest. The stimulus duration was 1 s, that is, less than one gait cycle consisting of 2 steps was shown on each trial. The stimuli were presented either in an upright orientation or inverted 180° (mirror-image, see Fig. 1B). In 3 separate runs, participants were shown a set of 96 upright, computer-generated body motion stimuli (32 different displays in each run, in randomized order) with an equal number of walker-present and walker-absent displays. In 3 other runs, 96 inverted displays were presented. The order of runs was randomized. Each run was preceded by a 10-s exposure to the noncamouflaging walking figure presented with respective orientation. Participants used a confidence rating procedure to verbally judge the presence of a walker (1, confident in the presence of walker from 100 to 80%; 2, from 80 to 60%; 3, from 60 to 40%; 4, from 40 to 20%; and 5, from 20 to 0%). To avoid time pressure during performance of the task, participants were asked to start each trial by pressing a button on a keyboard. No immediate feedback was given regarding performance.

**Results**

For psychophysical data processing, the jackknife procedure was employed to calculate statistically unbiased parameters of receiver operating characteristic (ROC) curves from pooled rating-method data (Dorffman and Berbaum 1986). Data analysis was performed on the jackknife estimates of the area under the ROC curve (Az), a standard measure of sensitivity in signal detection theory (Macmillan and Creelman 2005). ROC analysis indicates higher susceptibility of the patients’ visual system to the camouflage of a point-light walker (Fig. 3A). As assessed by $\chi^2$ statistic that involved both the sensitivity index and the slope of the binormal ROC curve (Metz and Kronman 1980), patients with lateral cerebellar lesions had significantly lower sensitivity to body motion than healthy person-to-person matched controls without signs of cerebellar abnormality on an MRI scan ($\chi^2 = 11.44, P < 0.01$). Visual sensitivity in left lateral cerebellar patients was lower than in medial patients ($\chi^2 = 6.87$, $P < 0.05$). Patients with medial cerebellar lesions, however, did not significantly differ from matched controls ($\chi^2 = 1.95$, n.s.). Both control groups exhibited an equally high level of visual sensitivity ($\chi^2 = 1.36$, n.s.). No differences were found in the cognitive decision criteria (In $\beta$) between patients with medial and lateral cerebellar lesions as well as between the patients and controls. This indicates that it is a reduction in visual sensitivity that is responsible for poorer performance of patients with lateral cerebellar lesions.

As a control condition for visual sensitivity to body motion, we used upside-down presentation of the same point-light displays inverted 180° (mirror-image). Although an inverted display retains the same relational structure and amount of motion as an upright one, it is shown by earlier work that inversion severely impedes integration of the moving local dots into a point-light walking figure (Pavlova and Sokolov 2000; Tadin et al. 2002; Pavlova, Sokolov et al. 2006). The upside-down presentation has a number of advantages as a control for the visual body motion detection task. The most important of them is that manipulation with display orientation allows one to keep the same amount of sensory information available. The only difference between upright and inverted displays is that in upright displays, the trajectories of moving dots on the main limbs of the point-light walker correspond to body motion during human walking under natural conditions, and in inverted displays these trajectories contradict gravity forces. The human visual system is extraordinarily sensitive to the
gravity laws (Pavlova and Sokolov 2000; Shipley 2003) and even newborn chicks appear to have a predisposition for gravity forces in point-light body motion displays (Vallortigara and Regolin 2006). As expected, display inversion resulted in an overall substantial reduction of sensitivity so that it no longer differed between patients with lateral lesions and matched controls ($\chi^2 = 5.13, \text{n.s.};$ see Fig. 3B). No difference in sensitivity to upside-down motion displays occurred between medial cerebellar patients and matched controls ($\chi^2 = 0.04, \text{n.s.}$), as well as between the control groups ($\chi^2 = 4.09, \text{n.s.}$). These findings indicate that impaired performance of the patients with lateral cerebellar lesions on the detection task under upright stimulus presentation was caused by difficulties in the visual processing of body motion.

Discussion

Most recent neuroanatomical, neuroimaging and neuropsychological lesion studies suggest that the cerebellum is involved in diverse networks subserving higher cognitive functions. However, cerebellar substructures underlying these functions have not yet been identified. The right temporal cerebral cortex, and, in particular, the STS, is repeatedly reported to substantially contribute to the visual processing of body motion (e.g., Grossman et al. 2000; Beauchamp et al. 2003; Pelphrey et al. 2003, 2005; Zacks et al. 2006). Human magnetoencephalography reveals a specific pattern of oscillatory response to a point-light walker that rapidly unfolds in time over the left occipital (100 ms) and bilateral parietal (130 ms) regions, and finally peaks over the right temporal (170 ms) cortex (Pavlova et al. 2004, 2006). By contrast, a peak of activation over the right temporal regions is absent in response to an inverted point-light walker that turns to become unrecognizable. We expected that because of contralateral connections to the cerebellar regions, the right temporal cortex may interact with the left cerebellum.

The present data point to left lateral cerebellar involvement into the action observation network. These findings substantially extend brain imaging data in healthy adults revealing cerebellar activation during visual processing of point-light body motion (Grossman et al. 2000; Vaina et al. 2001; Ptito et al. 2003). Previous fMRI and PET data, however, do not reach consensus as to cerebellar substructures that are engaged in visual processing of body motion. The main outcome of the present work indicates that damage to the left lateral cerebellum causes a pronounced deficit in the visual sensitivity to human locomotion, whereas medial lesions do not substantially affect visual perception of human walking. These data were obtained with rigorous psychophysical methodology in patients that were selected for similar lesion extent and (within a group) for similar lesion topography. The finding dovetails with previous fMRI data inasmuch as the lateral cerebellum appears to be selectively activated during visual processing of point-light biological motion (Vaina et al. 2001).

Although the right temporal cortex is reported to be activated more strongly and frequently during visual processing of body motion (Grossman et al. 2000; Beauchamp et al. 2003; Pelphrey et al. 2003; Grossman et al. 2004, 2007; Pelphrey et al. 2005; Zacks et al. 2006), brain imaging and lesion data suggest that the left parieto-temporal cortex might also be involved (Bonda et al. 1996; Grossman et al. 2000; Grossman and Blake 2002; Saygin et al. 2004; Saygin 2007). Therefore, engagement of the right cerebellum in visual processing of human actions and locomotion remains to be clarified in future research.

Keeping in mind that the cerebellum is heavily involved in movement production, one can assume that it might also be interconnected with the mirror neuron system, which has been considered as a core for understanding the actions and intentions of others (Iacoboni and Dapretto 2006). This system is thought to bridge the gap between the physical self and social perception through motor-simulation mechanisms. The action representation system contributes to the perception and understanding of actions and intentions of others; that is when we observe others, we mentally simulate the actions we see (Rizzolatti and Fabbri-Destro 2008).

Compromised visual processing of body motion in left lateral cerebellar patients suggests that this part of the cerebellum may be of particular importance for social perception through body motion and understanding of others’ actions. In accord with this view, recent brain imaging data reveal cerebellar involvement in visual social cognition through body motion. PET indicates that the left lateral cerebellum is activated during
recognition of dynamic, but not static, emotional facial expressions (Kilts et al. 2003). Recent fMRI data show that left lateral cerebellar activation is observed during perception of dynamic, as compared to static, emotional expressions of the whole body (Grèzes et al. 2007). This observation also agrees with reports that autistic individuals known for their impairments in social cognition have substantial alterations in the neuroanatomy and connectivity of the cerebellum, such as reduced white matter volume (McAlonan et al. 2005).

Healthy perceivers are able to reliably infer emotions, desires, intentions, and dispositions represented only through body motion dynamics (Heberlein et al. 2004; Chouchourelou et al. 2006). Furthermore, observers can discriminate between deceptive and true intentions conveyed by body dynamics, and true information is precisely detected despite misleading endeavors (Runeson and Frykholm 1983). When observers reveal false intentions in others’ actions, elevated fMRI activation is found among other regions in the right STS and the left lateral cerebellum (Grèzes et al. 2004). Obviously, a proper functioning of the brain network involved in social perception through body motion depends on intact communication between several areas throughout the brain. Future research will shed light on the role of the cerebellum for social cognition through body motion.

A further step toward uncovering localization of cerebellar regions and their connections to other brain structures engaged in the network underlying visual processing of body motion would be a combination of psychophysical methods with an analysis of functional brain activity and diffusion tensor imaging. Overall, the present findings offer new insights into the functional role of the cerebellum in normalcy and pathology beyond the purely motor domain.

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