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Action perception recruits the cerebellum and is impaired in patients with spinocerebellar ataxia

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Our cerebellum has been proposed to generate prediction signals that may help us plan and execute our motor programmes. However, to what extent our cerebellum is also actively involved in perceiving the action of others remains to be elucidated. Using functional MRI, we show here that observing goal-directed hand actions of others bilaterally recruits lobules VI, VIIb and VIIIa in the cerebellar hemispheres. Moreover, whereas healthy subjects (n = 31) were found to be able to discriminate subtle differences in the kinematics of observed limb movements of others, patients suffering from spinocerebellar ataxia type 6 (SCA6; n = 21) were severely impaired in performing such tasks. Our data suggest that the human cerebellum is actively involved in perceiving the kinematics of the hand actions of others and that SCA6 patients' deficits include a difficulty in perceiving the actions of other individuals. This finding alerts us to the fact that cerebellar disorders can alter social cognition.

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Abbreviations: SARA = Scale of the Assessment and Rating of Ataxia; SCA6 = spinocerebellar ataxia type 6; SI = primary somatosensory cortex

Introduction

The ability to perceive hand actions of others plays a key role in our ability to learn fine motor skills from conspecifics and interact successfully with them in cooperative and competitive settings. Cerebral cortical regions involved in motor control, including the premotor cortex and inferior parietal cortex, where mirror neurons were found in the monkey (di Pellegrino *et al.*, 1992; Gallese *et al.*, 1996; Rizzolatti *et al.*, 1996; Kohler *et al.*, 2002;

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Keysers *et al.*, 2003; Fogassi *et al.*, 2005; Rozzi *et al.*, 2008), as well as the primary somatosensory cortex (SI) (Gazzola and Keysers, 2009; Caspers *et al.*, 2010; Keysers *et al.*, 2010), have all been shown to be necessary for extracting subtle information from the observed kinematics of hand actions (Urgesi *et al.*, 2014; Keysers *et al.*, 2018). A powerful task to reveal the impact of disturbing these cortical regions requires participants to judge the weight of an object lifted by another individual (Pobric and Hamilton, 2006; Hamilton *et al.*, 2007; Valchev *et al.*, 2017). This task depends on the ability to transform subtle kinematic cues into a weight estimate in that participants rely on the velocity of movement when the object is lifted from the table to determine the weight of the object (Hamilton *et al.*, 2007). Perturbing activity in the premotor cortex and SI disrupts the ability to perceive the weight (Pobric and Hamilton, 2006; Valchev *et al.*, 2017), suggesting a causal role of premotor and somatosensory region in action perception.

The cerebellum is a key partner of these neocortical brain regions during motor control, where its role is well established (Kelly and Strick, 2003; Gao *et al.*, 2018). It is perhaps not surprising that some have speculated that the cerebellum may also play a role in the perception and prediction of the kinematics of observed hand actions. Specifically, it has been proposed that the cerebellum could leverage its forward models (i.e. neural computations that transform motor signals into expected sensory consequences) to predict the actions of others (Miall, 2003; Wolpert *et al.*, 2003; Fuentes and Bastian, 2007; Gazzola and Keysers, 2009; Rizzolatti and Sinigaglia, 2010). Although this proposal is intuitively appealing, we still have little evidence for the cerebellum being a reliable and even necessary node of the action observation network (Sokolov *et al.*, 2017). This is because functional MRI evidence for its recruitment during action observation is mixed, and very few neuromodulation or lesion studies have explored the impact of cerebellar disruptions on hand action observation.

With a few exceptions, imaging studies on action perception have typically focused on the involvement of the neocortex, leaving the information about cerebellar activity limited to what the field of view of functional MRI of these studies usually included, i.e. the dorsal cerebellum (Aziz-Zadeh, 2006; Gazzola *et al.*, 2007*a*, *b*; Catmur *et al.*, 2008; Gazzola and Keysers, 2009; Agnew *et al.*, 2012; Brunner *et al.*, 2014; Plata Bello *et al.*, 2014; Di Cesare *et al.*, 2015; Jelsone-Swain *et al.*, 2015; Thomas *et al.*, 2018). Several other experimental studies fail to observe cerebellar activation to hand action observation (Iacoboni *et al.*, 1999, 2001; Buccino *et al.*, 2004; Orr *et al.*, 2008; Rocca and Filippi, 2010; Jastorff *et al.*, 2012; Sasaki *et al.*, 2012; Horan *et al.*, 2014). This inconsistency is also reflected in meta-analyses of action observation studies, with some finding no (Caspers *et al.*, 2010) or very limited cerebellar activations (Molenberghs *et al.*, 2012), and others finding several clusters (Van Overwalle *et al.*, 2014). In their extensive meta-analysis, Van Overwalle *et al.* found that only 28% of the reviewed studies investigating action observation report cerebellar activity. The degree to which these inconsistencies depend on data acquisition and data analysis pipelines not optimized for the cerebellum is difficult to estimate *post hoc*, and experiments that optimize methods for the cerebellum, assess the reliability of activations in individual participants, and assess replicability across studies are required. The first part of this manuscript will therefore present four functional MRI experiments that map and replicate the recruitment of cerebellar voxels during hand action observation using MRI acquisition and analysis methods optimized for the cerebellum. These studies highlight that lobules VI and VIII of the cerebellar hemispheres are consistently recruited by action observation.

However, to establish whether the cerebellum causally contributes to hand action observation, its activity must be perturbed and the impact on action perception measured. Unfortunately, only two studies have taken that route so far. First, Sokolov *et al.* (2010) showed that four patients with tumours in the left lateral cerebellum (but not those with lesions in the vermis) were impaired in their ability to detect whether a point-light walking motion was embedded in random dot motion of that locomotor activity. However, the motor control of routine walking and of skilled hand actions is fundamentally different, as demonstrated by the fact that lesioning the pyramidal tract that transmits the cortical output to the spinal cord leaves routine treadmill walking unaltered (Eidelberg and Yu, 1981), but severely impairs skilled hand actions (Forssberg *et al.*, 1999; Duque *et al.*, 2003; Hermsdörfer *et al.*, 2003). Second, Cattaneo *et al.* (2012) tested the involvement of the cerebellum in the perception of action sequences. They showed eight participants affected by cerebellar ischaemia sets of four still photographs taken during an action (e.g. opening a bottle and pouring a glass of water). One of the four pictures did not fit the temporal sequence of the action, and the task was to identify which one was the intruder. They found the performance of five of the cerebellar patients to be below the range of the 16 healthy control subjects. While this study does not explore the processing of the subtle kinematic cues, it provides the first evidence that cerebellar impairments can affect the ability of participants to identify acts not belonging to a particular action sequence. However, while dozens of studies in hundreds of participants establish that premotor and parietal regions of the neocortex are necessary for the optimal perception of observed actions (Urgesi *et al.*, 2014; Keysers *et al.*, 2018), the necessary role of the cerebellum in hand action observation hinges on a single study with eight patients that does not directly test kinematics. In the second part of the study we therefore aimed to provide new evidence for a contribution of the cerebellum to action perception, and the first evidence for its role in processing subtle kinematic cues during hand action perception. To this aim, we tested the ability of 21 patients with spinocerebellar ataxia of subtype 6 (SCA6) to detect the weight of a box by

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observing the kinematics of a hand lifting the box in a video setting. SCA6 is a rare late-onset neurodegenerative disorder characterized by ataxia and associated with a loss of Purkinje cells in the cerebellum (Du *et al.*, 2013). A voxel-based morphology study points to loss of grey matter in the hemispheres of lobule VI (Rentiya *et al.*, 2017) as being the primary cause of the upper limb ataxia—adjacent to regions in which we found cerebellar activations to action observation in part one of our study. Task performance was compared with that of 31 age-matched control subjects. Participants were tested in (i) a condition in which a sleeve on the actor's arm occluded muscle shape information, forcing participants to focus on the arm's kinematics to judge the weight of the box (Sleeve); and in (ii) a condition in which the sleeve was removed to reveal information on the appearance of muscle contractions, which complements the arm's kinematic information (NoSleeve). Comparing the two groups in the Sleeve condition will reveal whether the cerebellum is necessary for kinematic processing. Comparing the gain in performance across the two conditions (i.e. the NoSleeve − Sleeve performance difference) across groups will reveal whether the cerebellum is necessary to extract additional information from biological shape.

The two main aims of our work are therefore to establish: (i) whether and where hand action observation reliably activates the cerebellum; and (ii) whether perturbations of cerebellar functioning impair the ability to process the kinematic and/or shape of observed actions.

Materials and methods

Experiments and participants

See Table 1 for an overview. Experiment 1 was aimed at localizing cerebellar activity to action observation using different analysis pipelines, and at comparing the results between pipelines and those found in the literature. Experiments 2 and 3 tested the replicability of the results of Experiment 1 on two independent samples of participants, and on a different MRI scanner. Experiment 4 tested the impact of the weight discrimination task on the previously identified action observation network, and Experiment 5 was aimed at directly testing the involvement of the cerebellum in action perception by comparing the accuracy in weight estimation between SCA6 patients and matched controls.

All tested healthy participants had a normal or corrected to normal vision, and none had a history of neurological conditions or treatments. The participants tested in the MRI also met MRI safety requirements.

The SCA6 patient group was recruited in collaboration with the Department of Neurology at the Erasmus MC Rotterdam (Supplementary material). The severity of disease progression was clinically assessed by a licensed neurologist using the Scale of the Assessment and Rating of Ataxia (SARA) (Schmitz-Hubsch *et al.*, 2006; Saute *et al.*, 2012). SARA includes eight items (gait, stance, sitting, speech disturbance, finger chase, nose-finger test, fast alternating hand movements and heel-shin slide) reflecting neurological manifestations of cerebellar ataxia (Weyer *et al.*, 2007). SARA scores range from 0 to 40, with higher scores corresponding to higher progression. The average SARA score for our patients' group (n_{SARA} = 17) was 11.38 ± 5.75 [standard deviation (SD); range: 2 to 21.5]. The 31 healthy participants that were recruited as the control group, matched the SCA6 group for age [$t(50) = 0.96$, $P = 0.34$], handedness (SCA6: 19 right-handed and two left-handed, Controls: 27 right and four left-handed, Yates corrected $\chi^2 = 0$, $P = 0.94$) and gender (SCA6 15 female: 6 male, Controls 15 female: 16 male, Yates corrected $\chi^2 = 1.86$, $P = 0.17$). However, our patient group contained fewer males numerically, an issue that is addressed in the control analyses. Control subjects did not receive a clinical assessment.

All participants signed an informed consent in accordance with the Declaration of Helsinki. The functional MRI study protocols were approved by the medical ethical committee of the University of Groningen (METc2012/380), the ethics review board of the University of Amsterdam (2015-BC-4697), the Academic Medical Center of Amsterdam (W15_243#15.0288), and the clinical study protocol was approved by the Medical Ethical Committee of the Erasmus MC Rotterdam (MEC-2013-095).

Stimuli, tasks and paradigms

Action observation task

During the observation task participants watched 39 unique videos of a human right hand interacting with objects displayed on a table (ActionOBS) (Fig. 1A). The 39 control videos displayed a hand movement without a meaningful object interaction (CtrlOBS). Experiments 1 and 2 also contained a third static condition, in which the hand rested close to the object (Arnstein *et al.*, 2011; Valchev *et al.*, 2016). This static condition was not included in Experiment 3, and therefore not included in the group analyses. Conditions were randomized across participants and presented using the Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) in a single functional MRI run. Participants were instructed to pay close attention to the videos shown.

Weight discrimination task

Participants performed a two-alternative forced-choice task, in which at every trial, participants had to choose in which of the two presented videos the heavier object was lifted. The 4-s video clips showed a human arm lifting an object. To avoid participants deducing the weight from object movement only (e.g. differences in object shaking during the lifting phase), a black panel occluded both the object and the hand from vision. To disentangle whether the contribution of cerebellum mainly comes from computation of action kinematics or from arm shape information, two versions of the task were created: (i) in half of the trials, the arm lifting the object was sleeved thus making the kinematic of the arm the only information available to perform the task (Sleeve); and (ii) in the other half, the arm was uncovered thus allowing both kinematic and shape information to be used (NoSleeve) (Fig. 1B). During the video recording, the actor was instructed to lift one of three weights (2850 g, 900 g and 180 g) within 4 s. A metronome was used to time the lift, and a reference line was marked on the wall in front of the actor to help maintain the same lifting height

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Table 1 Experiment overview

Experiment	Number of subjects incl. (recruited), subject type	Mean age ± SD [range]	Gender F, M	Technique	Task	Experimental aim	Relevant figures and tables
Experiment 1, AO	31 (35) healthy	23 ± 4 [19–40]	21, 10	fMRI	Action observation	Localize cerebellar voxels responding to action observation	Fig. 2, Tables 2 and 3, Supplementary Figs 1, 2, 6 and 7, Supplementary Tables 1–4
Experiment 2, AOrep1	25[a] (25) healthy	25.2 ± 4 [19–32]	13, 12	fMRI	Action observation	Replicability of cerebellar activations to action observation	Fig. 2, Tables 2 and 3, Supplementary Figs 1, 2, 6 and Supplementary Tables 1–4
Experiment 3, AOrep2	23 (23) healthy	25.5 ± 3.6 [21–33]	11, 12	fMRI	Action observation	Replicability of cerebellar activations to action observation	Fig. 2, Tables 2 and 3, Supplementary Figs 1, 2, 6 and 7, Supplementary Tables 1–4
Experiment 4, WD	25[a] (25) healthy	25.2 ± 4 [19–32]	13, 12	fMRI	Weight estimation	Localize cerebellar activations to the weight discrimination task and compare them with Experiments 1–3	Fig. 3, Supplementary Table 4 and Supplementary Fig. 5
Experiment 5, SCA6	19_{WD}, and 17_{SARA} (21) SCA6	62 ± 7 [49–80] 60.8 ± 7 [49–68]	WD 14, 5 SARA 12, 5 Total 15, 6	Behav + eye tracking (n = 4)	Weight estimation	Investigate whether cerebellar deficits are reflected in decreased accuracy in perception	Fig. 4 and Supplementary Fig. 3
	31 healthy	61 ± 7 [43–74]	15, 16	Behav + eye tracking (n = 7)	Weight estimation		
Experiment 6, EMG	10 healthy	32.5 ± 4.3 [29, 42]	4, 6	FDI EMG	Action observation	Identify whether stronger EMG activity during ActionOBS could explain brain activity in motor regions	Supplementary Fig. 4
Experiment 7, fMRI	7 (7) healthy	26 ± 4.5 [21–33]	5, 2	fMRI	Action observation and eye movements	Test whether differences in eye movements between ActionOBS and CtrlOBS alone could explain the stronger activity for ActionOBS	Supplementary Fig. 6

All groups of participants are independent except [a]those in which the same 25 participants underwent both the passive observation and the weight estimation task in separate sessions. In Experiment 1, four participants were excluded from the statistical analysis: two due to excessive head motion (displacement of >3.5 mm voxel dimension), one reported sleepiness, and one because of image distortion. In Experiment 5, two participants were excluded from the weight lifting task because pre-symptomatic, and two more were excluded from the correlation with SARA because they did not have SARA scores. Experiments 6 and 7 are control experiments aimed at addressing some possible confounds. AO = action observation; AOrep = action observation replication; FDI = first dorsal interosseous; fMRI = functional MRI; WD = weight discrimination.

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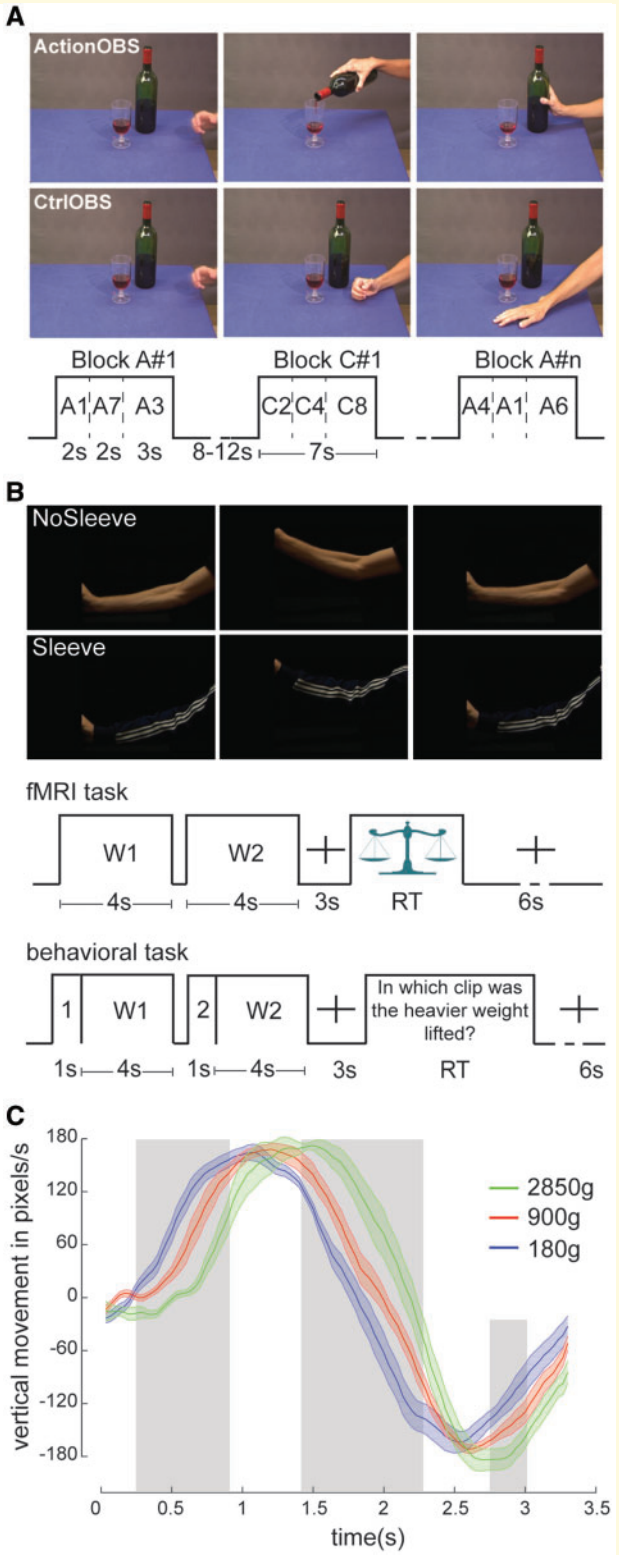

Figure 1 Experimental tasks. (**A**) Action observation task. Example of 1 of 39 possible actions and its control, followed by the task structure. A = action; C = control; Ctrl = control; OBS = observation. The ActionOBS and CtrlOBS videos were grouped in blocks of 7 s. Each block contained three actions from the same condition, with a total of 13 blocks for each condition. Blocks were separated by a fixation cross for a random period of 8–12 s, displayed on a background that was visually similar to the table. (**B**) throughout all videos. The actor was aware of the object weight to avoid hesitation in the lifting. Videos were recorded using a digital video camera (Sony DSRPDX10P) and edited using Adobe Premiere Pro (Version CS5, Adobe System Incorporated, San Jose, USA). As expected, the differences in weight lead to differences in the kinematic of the video-recorded actions that allow viewers to deduce the weight (Fig. 1C) (Hamilton *et al.*, 2007). Clips showing the same lifted weight were never paired. In half of the trials the heaviest object was lifted first, in the other half as second. The order was randomized in Psychopy2 (Peirce, 2009). After the second clip, the task instruction was presented until the subject indicated his/her response. Before the beginning of the task participants performed four training trials.

Some minor task differences were present between Experiments 4 and 5 (Fig. 1B).

Experiment 5: Behaviour

Participants gave the response by pressing the arrow keys on a standard QWERTY keyboard using their right hand. Ninety-six trials were presented in total, and participants had the option to take a short voluntary break after the first half of the trials.

Experiment 4: Functional MRI

Participants indicated their responses by means of an MRI compatible button box. Participants used their left hand to select the first clip and their right hand to select the second. Stimuli were presented using Presentation® software. For the functional MRI experiment, a numerosity task was additionally introduced and intermixed with the weight discrimination task. Participants had to estimate and compare the number of moving dots shown in Videos 1 and 2 instead of weight. The movement of the dots followed the kinematic of the arm presented in the Sleeve and NoSleeve conditions, but the arm was not visible. As an error occurred in the randomization of this condition, and this task was not performed by the SCA6 group, the numerosity condition was not included in the group analyses. Seventy-two trials were presented in total (24 for each of the three conditions).

Figure 1 Continued

Weight discrimination task. Frame extracted from the NoSleeve (*top*) and Sleeve (*bottom*) weight lifting condition, followed by the trial structure for the functional MRI (*top*) and behavioural experiments (*bottom*). In the functional MRI (fMRI) task the window of time participants were requested to answer was indicated by a weighing scale. In the behavioural task, clips were preceded by the number 1 or 2 denoting whether it was the first or second clip of the pair. The sentence following the video was translated from Dutch for illustration purposes. RT = participant's reaction time. (**C**) Kinematic analysis of the weight-lifting videos. Mean ± standard error of the mean (SEM) of the vertical velocity of the forearm as a function of weight relative to the onset of the videos, averaged over the Sleeve and NoSleeve conditions. Moments in which velocity carries significant information about the weight are marked in grey, as revealed by a one-way ANOVA comparing velocity across the three weights at $P < 0.01$.

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Functional MRI data acquisition

All MRI datasets included an anatomical scan. Experiment 1 included one functional scan of the action observation task. Experiments 2 and 3 aimed at comparing the effect of different numbers of simultaneous slice acquisition on task-based functional MRI, and included four and five functional scans of action observation, respectively. The results of this comparison are the subject of a separate manuscript (Bhandari *et al.*, 2019). As participants of Experiment 1 only saw the videos once, we only included the first view of the action observation task, independently of the number of simultaneously acquired slices. Experiment 4 included two functional runs of the weight lifting task. These two runs were randomly presented between the four observation runs of Experiment 2. The scanning parameters were chosen to achieve a coverage of the entire cerebrum and cerebellum (Supplementary Table 1).

Localization of cerebellar activations, impact of different analysis pipelines and replicability

The impact of different pipelines on cerebellar task-based responses was analysed on data from Experiment 1. The four considered pipelines mainly differed in the order in which the preprocessing and first level subject statistics were computed, and in the normalization template. Because the comparison revealed a no clear advantage of using pipelines optimized for the cerebellum compared to the traditional one, the method and results of this comparison are presented in the Supplementary material, Supplementary Tables 2 and 3 and Supplementary Fig. 1.

All of the analyses included in the main text therefore follow the traditional approach that includes: slice-time correction, realignment of functional images to the computed mean, co-registration of the anatomical image to the mean, whole brain normalization to the MNI template (final voxel size: 2 × 2 × 2 mm) based on the parameter generated during the segmentation of the co-register anatomy, a smoothing with a 6 mm full-width at half-maximum Gaussian kernel followed by a general linear model (GLM). Analyses testing the possibility of activation leakage between the anterior cerebellum and the temporal cortex due to smoothing are reported in the Supplementary material.

For Experiments 1–3, the GLM included two standard box car predictors that modelled the ActionOBS and CtrlOBS video presentation. Experiments 1 and 2 also included a predictor modelling the static conditions. All predictors were convolved with the canonical haemodynamic response function (HRF). The last six regressors of no interest included the displacements and rotations along the three axes, determined during image realignment. The ActionOBS−CtrlOBS contrast was computed at the subject-level to generate action-specific activations for observation. Analyses of variance on the ActionOBS−CtrlOBS contrast values from Experiments 1–3 were also implemented to directly compare the results of the three experiments to each other (within-subjects ANOVA) as well as to baseline (one-way ANOVA).

All analyses were run in SPM8 and 12 (Wellcome Trust Centre for Neuroimaging, UCL, UK) using MATLAB 7.14 (The MathWorks Inc., Natick, USA) with a bounding box size-adjusted to include the entire cerebellum [−90 −126 −72; 91 91 109], complemented by custom MATLAB scripts. Unless specified otherwise, all analyses were estimated within the cerebellar mask using the cerebellar anatomical map from the Anatomy toolbox (http://www.fz-juelich.de/ime/spm_anatomy_toolbox) (Geyer *et al.*, 1996, 1999, 2000; Amunts *et al.*, 1999; Grefkes *et al.*, 2001; Geyer, 2004; Eickhoff *et al.*, 2005, 2006, 2007; Caspers *et al.*, 2006; Choi *et al.*, 2006). The Anatomy toolbox was also used to define regions of interest, and guide anatomical descriptions of clusters of activity.

Unless otherwise specified, all statistical maps were thresholded at $P_{FWE} < 0.05$ with a minimal cluster size of 10 voxels. We chose peak-level familywise error (FWE) correction as we wished to (i) interpret activation of individual voxels, and, motivated by the inconsistencies of cerebellar activations in the literature; (ii) to limit the risks of type I errors.

To investigate the consistency in location of voxels responding to action observation between participants and studies, we computed consistency maps (Gazzola and Keysers, 2009) (Supplementary material). However, as the consistency maps cannot confirm that voxels responding to action observations are present in all participants, we counted the number of activated voxels within each participant. This counting was done separately for the four cerebellar anatomical regions of interest (left and right lobule VI, and VIIb/VIIIa) shown to be involved in the execution of complex actions (Schlerf *et al.*, 2010), and for the cerebellum as a whole. Additionally, lobule V was used as a control region as it has been shown not to differentiate simple from complex actions. To compare the reliability of cerebellar activations with that of the cortex, the counting was done for three additional cortical regions, typically associated with the action observation network (Gazzola and Keysers, 2009; Caspers *et al.*, 2010; Molenberghs *et al.*, 2012): the premotor area [Brodmann area (BA) 44], the inferior parietal complex (PF) and the SI.

Localization of the weight discrimination task

The GLM of Experiment 4 included eight boxcar predictors: three modelled the video presentation (i.e. from the beginning of Video 1 to the end of Video 2) associated with the Sleeve, NoSleeve and numerosity conditions; two captured the participant's responses at the time the weighting scale was presented separately for the left and right hand; one captured text information given to our participants at the beginning and the end of the each session; one included button presses that happened outside the response window; and one included the four videos used for training (only for the first session). The six head motion parameters were again added as co-variates of no interest. Analyses of variance were used to compare the Sleeve and NoSleeve conditions to each other (within-subjects ANOVA), and to baseline (one-way ANOVA). As for Experiments 1–3, unless otherwise specified, the ANOVAs were computed within the cerebellar mask, at $P_{FWE} < 0.05$.

To test whether the videos used for the weight estimation task elicited activity in the areas to be found active for general action observation, an additional GLM was computed within a binary mask obtained by the global null conjunction of Experiments 1, 2 and 3 [$Exp1_{ActionOBS\text{-}CtrlOBS}$ OR $Exp2_{ActionOBS\text{-}CtrlOBS}$ OR $Exp3_{ActionOBS\text{-}CtrlOBS}$] ($t_{FWE} = 2.06$) from the one-way ANOVAs that included the ActionOBS–CtrlOBS from all three experiments. Results are shown at $P_{FWE} < 0.05$.

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Analyses of behavioural data

Task performance scores were calculated as proportion of correct responses. We checked their normality using the Lilliefors test. Performance for the Sleeve and the NoSleeve–Sleeve difference were normally distributed (both $P > 0.12$). The performance in the NoSleeve condition and the average score of Sleeve and NoSleeve violated normality (both $P < 0.002$). Accordingly, we used non-parametric tests as our main approach, and parametric analyses (ANOVAs and Bayesian analyses) were only used to supplement analyses for the Sleeve and NoSleeve–Sleeve difference.

Control experiments

To explore whether visual cerebellar activity reflects differential motor activity, we recorded EMG activity from the right hand while participants viewed ActionObs and ActionCtrl vidoes (Supplementary Fig. 4). To explore the effect of eye movements, we measured eye tracking data from four patients and seven healthy subjects for the weight discrimination task (Supplementary material) and also functional MRI activity while participants viewed the ActionObs and ActionCtrl videos while fixating a cross, and while performing eye movements without the action videos (Supplementary material and Supplementary Fig. 6).

Data availability

Data are available online at https://openeuro.org.

Results

Localization of action observation activations in the cerebellum and their reliability

Viewing goal-directed hand actions compared to control stimuli (ActionOBS–CtrlOBS) in Experiment 1 bilaterally recruits lobules VI, VIIb and VIIIa of the cerebellar hemispheres (Table 2, Fig. 2A, Supplementary Fig. 1 and Supplementary material).

Overlapping our activations with action observation maps from the meta-analysis of Van Overwalle *et al.* (2014) (blue clusters of Fig. 2A) reveals only a small portion of the right lobule VI is common between the two maps. To test whether the limited overlap is due to subtracting our control condition, we overlapped the meta-analysis map with a global null conjunction of our conditions (i.e. ActionOBS OR CtrlOBS, $P_{FWE} < 0.05$, $t = 2.8$). The overlap remains limited to right lobule VI (Fig. 2B).

Considering this inconsistency, we (i) replicated the experiment on a different scanner in two new groups of participants; and (ii) explored how many of our participants have activations in the cerebellum.

Replicating the analysis in new participants confirms the cerebellar recruitment, despite using different scanners and sequences (Fig. 2C–E and Tables 2 and 3).

Looking at individual participants reveals that all but four (all from Experiment 1) of the 79 participants have significant activations to the ActionOBS–CtrlOBS contrast when tested at $P < 0.001$ ($t = 3.1$) within the cerebellum (green in Fig. 2G). The majority (68/79, 86.1%) additionally had >10 voxels activated (Fig. 2G and Supplementary Table 4) and most had at least 10 voxels in each of the cerebellar lobules identified in the group (regions of interest encompassing lobule VI or lobule VIIb + VIIIa) (black in Fig. 2G). A binomial distribution indicates that finding 10 or more voxels significant by chance at $P = 0.001$ in a region of interest of 2085 voxels (the largest region of interest we have) is highly unlikely ($P < 2 \times 10^{-5}$). To explore the spatial specificity of the activity in lobule VI further, we also performed this analysis for neighbouring lobule V, which harbours very few voxels responding in this contrast, with the majority of participants (78% for the left and 75% for the right lobule V) (grey in Fig. 2G and Supplementary Table 4) having none.

To compare the reliability of cerebellar activations with those of the cerebrum, we took three regions consistently associated with the action observation system, BA44, the PF complex and SI (Keysers and Gazzola, 2009; Caspers *et al.*, 2010; Molenberghs *et al.*, 2012), and counted activated voxels in these regions subject by subject (Supplementary Table 4). Chi^2 tests comparing the proportion of participants with zero voxels activated in the four cerebellar and six cerebral regions using Fisher's exact test in R indicates that for Experiments 1 and 2 the proportion with zero voxels activated is larger in the cerebellum (Exp1, $P = 0.001$; Exp2, $P = 0.004$; Exp3, $P = 0.86$). When combining all three experiments, the difference in proportion becomes highly significant ($P < 0.001$), with the cerebral regions of interest hosting significant voxels in a larger proportion of participants than the cerebellar regions of interest. Consistency maps indicate that the right lobule VI hosts the most consistently activated voxel, with 30 participants having significant activations in that specific voxel (Fig. 2F).

In addition to examining the contrast ActionOBS-CtrlOBS, we also extracted the average activity within our cerebellar regions of interest separately for ActionOBS and CtrlOBS (Supplementary Fig. 2).

To ensure that the observed cerebellar activity was not due to more imitative motor programs during ActionOBS than CtrlOBS, we collected EMG data while a new group of 10 participants watched the ActionOBS and CtrlOBS stimuli outside the scanner. Results show no difference in muscle activity across ActionOBS and CtrlOBS [$F(1,9) = 1$, $P = 0.33$, $BF_{10} = 0.1$] (Supplementary Fig. 4).

In summary, we found that our task reliably activates the cerebellum at the individual and group level, and across scanners and pipelines. In particular, we provide evidence for a consistent involvement of cerebellar lobules VI and VIIb and VIIIa in action observation, matching the involvement of these lobules during the execution of complex actions shown by Schlerf *et al.* (2010). Despite the replicability of our results

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Table 2 Cerebellar activations to ActionOBS–CtrlOBS for Experiments 1–3

Cluster size	Voxels in cyto	% Cluster	Hem	Cyto or anatomical description	% Area	Peak information			
						T	x	y	z
Experiment 1 ActionOBS–CtrlOBS $P_{FWE} < 0.05$, $t = 4.31$									
655	523	79.8	R	Lobule VI (Hem)	29	9.06	28	−54	−26
						7.72	20	−70	−22
	61.8	9.4	R	Area FG4	12.6	5.60	24	−44	−18
	14.4	2.2	R	Lobule VIIa crusI (Hem)	0.4				
	11.9	1.8	R	Area hOc3v [V3v]	1.4				
	11.9	1.8	R	Area FG1	4.8				
340	328.6	96.7	L	Lobule VI (Hem)	17.5	10.84	−28	−54	−26
						6.20	−20	−68	−24
249	103.4	41.5	R	Lobule VIIIa (Hem)	14.2	6.38	28	−60	−54
						6.08	20	−66	−54
						5.51	30	−54	−52
	97.1	39	R	Lobule VIIb (Hem)	14.8	8.23	16	−76	−50
	24.1	9.7	R	Lobule VIIIb (Hem)	3.4				
	12.9	5.2	R	Lobule VIIIa (Verm)	6.1				
162	85.9	53	L	Lobule VIIIa (Hem)	11.3	7.18	−22	−62	−52
	51.9	32	L	Lobule VIIb (Hem)	7.6	6.68	−18	−70	−50
						6.59	−16	−74	−48
	22	13.6	L	Lobule VIIIb (Hem)	3.6				
Experiment 2 ActionOBS–CtrlOBS $P_{FWE} < 0.05$, $t = 4.31$									
398	131.3	33	R	Lobule VIIIb (Hem)	18.3	8.66	20	−58	−52
	105.1	26.4	R	Lobule VIIIa (Hem)	14.5	8.10	12	−70	−48
	50.4	12.7	R	Lobule IX (Hem)	7.2				
	38.4	9.6	R	Lobule VIIb (Hem)	5.9	8.28	16	−72	−52
	20.5	5.2	R	Lobule VIIIa (Verm)	9.8				
262	205.9	78.6	R	Lobule VI (Hem)	11.4	7.69	30	−50	−24
						5.03	20	−68	−22
	44.9	17.1	R	Area FG4	9.2				
	10.4	4	R	Area FG3	1.6				
153	67.1	43.9	L	Lobule VIIIa (Hem)	8.8	7.53	−16	−66	−48
						4.78	−24	−52	−50
	53.4	34.9	L	Lobule VIIIb (Hem)	8.8	5.31	−18	−58	−52
126	94.8	75.2	L	Lobule VI (Hem)	5.1	7.01	−30	−48	−22
						5.40	−26	−56	−18
	23.4	18.6	L	Area FG4	4				
Experiment 3 ActionOBS–CtrlOBS $P_{FWE} < 0.05$, $t = 4.31$									
514	433.8	84.4	L	Lobule VI (Hem)	23.2	8.45	−26	−52	−18
						6.72	−18	−68	−22
	43.3	8.4	L	Area FG4	7.3				
	15.8	3.1	L	Lobule V (Hem)	2.2				
	12.9	2.5	L	Area FG3	1.6				
452	372.8	82.5	R	Lobule VI (Hem)	20.7	6.89	28	−52	−22
						5.96	18	−70	−22
						5.88	20	−68	−24
	61.3	13.6	R	Area FG4	12.5				
402	139.9	34.8	R	Lobule VIIIa (Hem)	19.3	8.34	26	−58	−54
	99.8	24.8	R	Lobule VIIIb (Hem)	13.9	5.32	18	−52	−50
	76.5	19	R	Lobule VIIb (Hem)	11.7	8.88	14	−74	−50
	22.6	5.6	R	Lobule VIIIa (Verm)	10.8				
85	47.8	56.2	L	Lobule VIIIa (Hem)	6.3	6.19	−10	−74	−50
	32.5	38.2	L	Lobule VIIb (Hem)	4.8				
75	35.1	44.5	L	Lobule VIIIa (Hem)	4.6	6.11	−22	−58	−46
						6.10	−32	−52	−50
	24.8	31.3	L	Lobule VIIIb (Hem)	4.1				

Regions with ActionOBS–CtrlOBS $\geqslant$ 4.31 labelled using SPM Anatomy Toolbox. Results are shown at $P_{FWE} < 0.05$ with cluster size >10 voxels.
Cyto = cyto-architectonic area; Hem = hemisphere.

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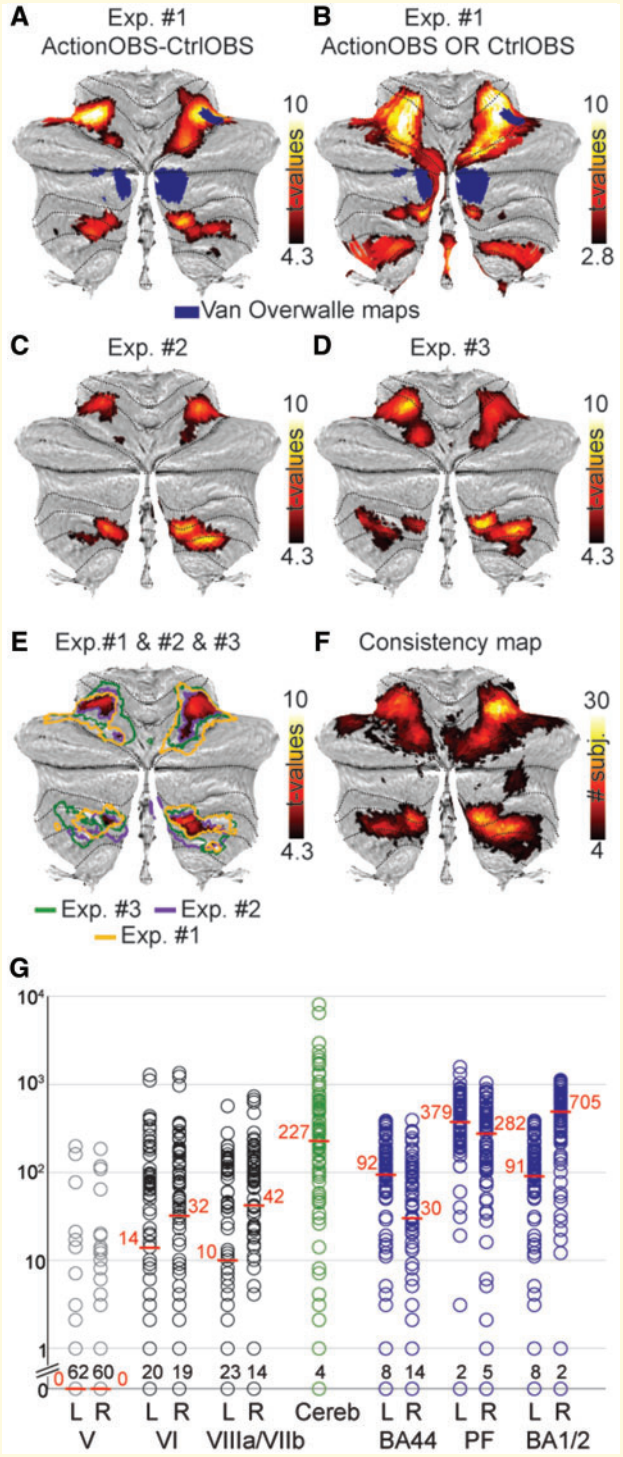

Figure 2 Reliability of cerebellar action observation activations. (**A** and **B**) In blue the maps presented by Van Overwalle *et al.* (2014), and the results of the ActionOBS–CtrlOBS contrast of Experiment 1 in the hot colour scale in (**A**) and of the global null conjunction ActionOBS OR CtrlOBS for Experiment 1 in (**B**), both at $P_{FWE} < 0.05$. (**C** and **D**) ActioOBS–CtrlOBS related activity for Experiments 2 and 3, respectively. $P_{FWE} < 0.05$, $t = 4.3$. (**E**) Activations common to Experiments 1–3. Yellow, blue and green contours indicate the borders of the clusters shown in **A**, **C** and **D** to facilitate the qualitative comparison. (**F**) Consistency map computed on the smoothed data for the ActionOBS–CtrlOBS ($P_{unc} <$ 0.001, $t = 3.1$) contrast across the three experiments. The hot scale indicates the number of participants for which a particular voxel was significantly activated by the ActionOBS–CtrlOBS contrast. (**G**) Circles indicate the number of significant voxels a given subject had in each of the four cerebellar clusters of interest (black), in the control lobule V (grey), in total in the cerebellum (green), and in three cortical regions also commonly activated by the ActionOBS–CtrlOBS contrast (blue). The median is indicated by the red lines and numbers. Data are presented on a logarithmic scale and the number of participants having no voxels in a particular cluster is indicated in black on the *x*-axis.

across three experiments, we did find that cerebral activations remain more consistent than the cerebellar activity across individuals, possibly explaining why smaller studies in the past may have failed to emphasize cerebellar activity.

Cerebellar activation to the weight discrimination task

Observing an arm lifting an object to judge its weight activates several regions of the cerebellum (Fig. 3A and B and Supplementary Table 6) ($P_{FWE} < 0.05$, $t = 2.8$). The responses to lifting movements overlap with the ALE meta-analysis maps (Van Overwalle *et al.*, 2014) beyond lobule VI, in both left and right lobule VIIa of crus I. Computing the GLM of the weight discrimination experiment within the global null mask of the previous three experiments shows that all clusters observed in Experiments 1–3 were activated by the observation of lifting movement (Fig. 3C and D and Supplementary Table 6).

What aspect of action observation is processed in the cerebellum? By disentangling the activity common to the Sleeve and NoSleeve conditions mentioned above (conjunction Sleeve and NoSleeve) from that specific to the NoSleeve condition (NoSleeve–Sleeve), we can attempt to identify regions involved in kinematic and shape processing, respectively. The eye-tracking maps from the control participants show that the two conditions are indeed explored differently (Supplementary Fig. 3A). When the arm was covered, participants focus similarly on the proximal and distal part of the arm [$t(12) = 1.523$, $P = 0.154$], but if no sleeve is present, participants focus significantly more on the proximal part of the arm [$t(12) = -9.482$, $P < 0.001$] that reveals shape information in the upper arm musculature. Results from the functional MRI data indicate that in contrast to the conjunction that revealed consistent cerebellar involvement for kinematic processing, at FWE correction at peak level nothing survives for both the Sleeve–NoSleeve and the NoSleeve–Sleeve contrast within the cerebellum ($t = 4.42$, $P > 0.05$), while 22 voxels in the fusiform area FG4 become apparent for the contrast NoSleeve–Sleeve when the analyses are run for the whole brain ($t = 5.4$, $P < 0.05$). Accordingly, the cerebellum is significantly recruited by the kinematic cues common to both conditions,

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Table 3 Comparison between Experiments 1, 2 and 3 in number of voxels and peak distance per cluster of activity

	Number of voxels				Min Euclidean distance		
	Exp1	Exp2	Exp3	Exp 1–3	Exp1, Exp2	Exp1, Exp3	Exp2, Exp3
Lob VI R	336	115	454	88	2.0	2.0	2.0
Lob VI L	537	216	391	202	7.5	2.8	4.0
LobVIIIa/ VIIb R	148	84	130	20	4.5	2.8	3.5
LobVIIIa/ VIIb L	223	198	265	120	4.9	6.3	7.2
Outside ROIs	179	344	299	56			

For each of the four cerebellar clusters, and for each experiment separately, the number of voxels surviving $P_{FWE} < 0.05$ for the contrast ActionOBS–CtrlOBS is reported. The fourth column reports the number of voxels counted within the conjunction of the three experiments. The last row indicates the number of cerebellar voxels not falling within the region of interest. Columns 5–7 indicate the minimum Euclidean distance between the activation-peaks identified belonging to the four clusters by the Anatomy toolbox for SPM. ROIs = regions of interest.

but not by the differential shape cue that the NoSleeve–Sleeve contrast situates in the ventral visual stream instead.

Cerebellar contribution to action perception

The Mann-Whitney U-test on task performance reveals a significant difference between SCA6 and control subjects for the Sleeve condition (n_{SCA6} = 21; n_{ctrl} = 31; U = 199.5; $P < 0.009$), in which participants depend on the kinematic information (Fig. 4A). The same test reveals that the gain of performance in the NoSleeve compared to the Sleeve condition (i.e. NoSleeve performance – Sleeve performance) does not differ significantly across groups (n_{SCA6} = 21; n_{ctrl} = 31; U = 274.5; $P > 0.34$). Not surprisingly, the two groups therefore also differ when the total performance is considered, including both the Sleeve and NoSleeve trials (n_{SCA6} = 21; n_{ctrl} = 31; U = 183; $P < 0.004$). Using *d'* instead of per cent correct leads to similar conclusions. To explore whether our pattern of findings, which includes a significant group difference for the Sleeve condition and a lack of significant group difference in the gain of performance, might indicate that the cerebellum contributes to kinematic but not shape processing, we performed a Bayesian *t*-test in JASP. The Bayes factors (BF) in favour of the alternative hypothesis Controls > SCA6 are BF = 14.7 (Sleeve) and BF = 0.19 (NoSleeve–Sleeve performance). Accordingly, we have strong evidence for a group difference in kinematic processing (Sleeve), and moderate evidence for a lack of difference for shape processing (NoSleeve–Sleeve).

To explore if this group difference in the performance could be due to the less than ideal matching on gender, we carried out two further analyses. First, we performed a parametric ANOVA on the performance in the Sleeve condition with two groups (SCA6 versus Controls) × 2 genders. The interaction of Gender × Group was not significant [$F(1,48) = 2.66$, $P = 0.11$], suggesting that the group difference does not depend on gender. Second, we created control groups that were exactly matched in gender to the SCA6 group by subselecting six males out of the 16 available in the control group, keeping all the 15 females. There are 8008 ways to subsample six males out of 16, and for each of them, we calculated the *P*-value for the group difference in total performance using the Mann-Whitney U one-tailed test. The median *P*-value across the 8008 subsamples was $P = 0.016$, and 7675 of the 8008 (96%) have $P < 0.05$ (Fig. 4B). This confirmed that compared to the majority of randomly subsampled, gender-matched control groups, the SCA6 group shows impaired performance in our task.

To explore whether there is a significant association between the severity of the degenerative disorder and the

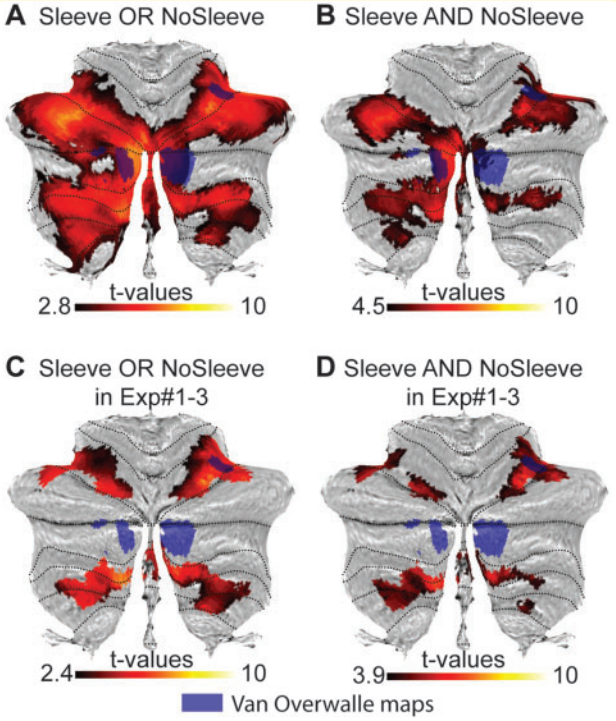

Figure 3 Functional MRI results of the weight discrimination task. (**A**) Voxels significantly activated by either the Sleeve (only kinematic information available) or the NoSleeve (both kinematic and shape information) condition (global null conjunction in SPM at $P_{FWE} < 0.05$, $t = 2.8$, min 10 voxels). In blue the clusters identified by Van Overwalle *et al.* (2014), as responding to action perception. (**B**) Voxels activated by both (conjunction-conjunction in SPM) the NoSleeve and Sleeve conditions ($P_{FWE} < 0.05$; $t = 4.5$, min 10 voxels). (**C**) Same as in **A** but within the clusters of activation found in Experiments 1–3 (Exp1 > 0 OR Exp2 > 0 OR Exp3 > 0). Results are shown at $P_{FWE} < 0.05$, $t = 2.8$, min 10 voxel. (**D**) Same as in **C** but within the clusters of activation found in Experiments 1–3 ($P_{FWE} < 0.05$; $t = 3.9$, min 10 voxels). All activations are shown on the flat map of the cerebellum offered by the SUIT toolbox.

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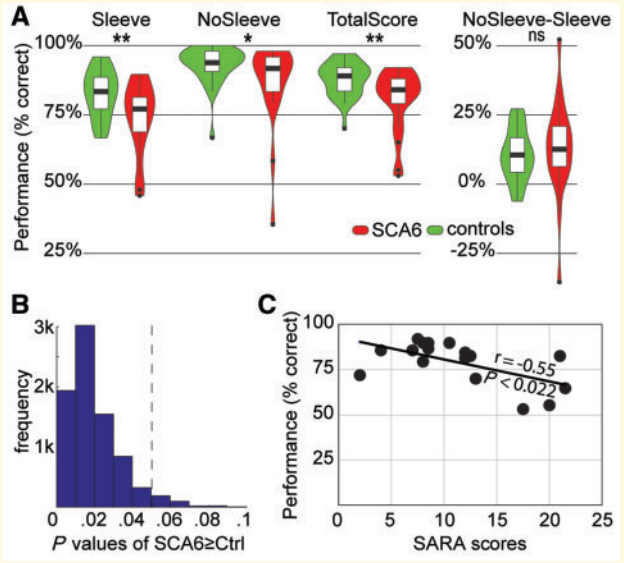

Figure 4 Behavioural results. (**A**) Violin plot of the performance (per cent correct responses) in the weight discrimination task for the 21 SCA6 patients (red) and 31 control subjects (green) for the different conditions. $^{*}P < 0.05$, $^{**}P < 0.01$ using Mann-Witney U tests to compare SCA6 versus controls group in each condition. (**B**) Distribution of *P*-values obtained from the 8008 possible subsamples of gender-matched control groups, again using the Mann-Whitney U-test to compare the total score (Sleeve and NoSleeve trials together) across groups. (**C**) The significant negative association between symptom severity (SARA) and total score in the weight perception task. The r-value reflects the non-parametric Spearman rank-order correlation. Higher SARA scores reflect more severe symptoms and predict more perceptual impairment. ns = not significant.

performance in our task, we calculated the Spearman rank order correlations between the total performance score and the SARA score for the 17 patients for which we do have the SARA score (Fig. 4C). We found that the association is significant: $R = -0.55$, $t(15) = -2.54$, $P < 0.022$.

Finally, to explore whether the perceptual impairment we observe in SCA6 patients would also be visible in implicit measures, we added eye-tracking in our last participants (four SCA6 and seven control subjects), which do not show any significant group difference (Supplementary material). Thus, even though the small sample size might have biased us to find only large group differences, the qualitatively similar pattern in the two groups suggests that SCA6 did not severely alter how subjects explored the stimuli in space and time.

Discussion

Our primary aims were (i) to explore whether and where the cerebellum is robustly activated by the observation of hand actions of other individuals; and (ii) whether disrupting the cerebellum leads to significant impairments in hand action observation.

Regarding activations, using scanning parameters that include the entire cerebellum (both in terms of field of view during acquisition and bounding box during analysis) we found that across three studies and a total of 79 participants, the cerebellum was consistently recruited by the contrast between goal-directed hand actions and meaningless movements of the hand close to an object. Single subject analyses confirmed that the cerebellum was recruited in all but four participants. More specifically, we found that activity is reliably induced in the lateral hemispheres of lobule VI, and in a cluster encompassing lobules VIIb and VIIIa. All these activations are bilateral. Without using smoothing, it is apparent that the dorsal cluster in lobule VI is distinct from activity in the ventral visual pathway, and is thus not the result of bleeding of activity from visual neocortical regions. Each of these clusters were found to be activated in the majority of individual participants. Together these results provide strong evidence that the cerebellum is consistently recruited by hand action observation.

This raises the question of why former studies failed to consistently report cerebellar activations. Our comparison of pipelines identifies two potential reasons: (i) up to SPM8, the default bounding box for analyses prevented the identification of some of the cerebellar clusters; and (ii) most studies focusing on the cerebrum have to choose between a larger field of view (i.e. more spatial coverage) versus a shorter acquisition time (i.e. increased task sensitivity), which often ends in favouring a smaller field of view therefore cutting out the cerebellum in at least some participants. At the second level of analysis, if part of the cerebellum is missing in the field of view for some of the participants, this region is entirely removed from the search volume on which statistical analyses are computed across all subjects. This may have further reduced the consistency with which cerebellar activity is reported. Finally, a comparison between the number of participants activating our cerebellar regions of interest compared to classic cerebral regions of interest such as BA44 or PF, shows that the cerebellar regions of interest indeed are slightly less reliably recruited, providing an additional factor. Overall, our three studies provide clear evidence that with proper measurement procedures and analysis pipelines, cerebellar recruitment during hand action observation can be demonstrated. The finding that these same regions are also activated when using a different, weight judgement task shows that this consistency does not depend on a specific task.

It is interesting that one of our complex action foci (ActionObs–ActionCtrl) was localized in the anterior part of lobule VI, which is where Schlerf and colleagues found activity when participants performed complex but not simple motor actions (Grodd *et al.*, 2001; Schlerf *et al.*, 2010). Our second focus was in the posterior inferior lobule VIIb expanding into VIIIa, adjacent to the secondary sensorimotor finger map (Grodd *et al.*, 2001; Schlerf *et al.*, 2015). Lobule V, associated with less complex actions,

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however did not show consistent visual activation, be it in the contrast or while comparing each condition against baseline (Supplementary Fig. 2). This distinction is reminiscent of that in the cerebral cortex, where M1 is not consistently recruited by action observation, while the premotor cortex, involved in more complex motor control, is (Gazzola and Keysers, 2009). That regions involved in motor control become recruited during observation is in line with the notion that cerebro-cerebellar loops involved in fine kinematic control of hand actions may also serve as a valuable system to process fine kinematics of observed actions (Miall, 2003; Wolpert *et al.*, 2003; Fuentes and Bastian, 2007; Gazzola and Keysers, 2009; Rizzolatti and Sinigaglia, 2010; Sokolov *et al.*, 2017). Alternatively, cerebellar activity to action observation could reflect automatic imitation of complex actions more than the control stimuli, with the cerebellum simply executing imitative motor programs. That EMG recordings show no difference in muscle activity across ActionObs and CtrlObs speak against this interpretation.

To explore whether the cerebellum is necessary for extracting information from the kinematics of the hand actions of others, we tested whether patients with SCA6 are impaired in a weight-lifting task that has been shown to depend on precise processing of hand movement kinematics (Hamilton *et al.*, 2007). Our results indicate that SCA6 patients are indeed impaired in their kinematic processing as borne out by a group difference in the Sleeve condition that impoverishes muscle shape information. This impairment was more pronounced in patients with more severe SCA6 symptoms. Interestingly, when we analysed the data of the stimuli without the sleeves, we found that muscle shape processing appears to be preserved, as Bayesian statistics confirm that the patients benefited from the additional muscle shape as much as the controls did. That both the SCA6 patients and their controls benefit from exposing the muscle shape in the NoSleeve condition speaks to the fact that our participants did use shape information. That they benefited equally suggests that shape information was not significantly influenced by SCA6, and fits with our interpretation that the SCA6 impairment in the sleeved condition could be explained by a perturbation of kinematic perception. These results complement the results of the only other study that has, to our knowledge, examined the impact of cerebellar damage in action observation (Cattaneo *et al.*, 2012), in that the two studies probed different aspects of hand action observation. In the task of Cattaneo *et al.* (2012), participants viewed four still frames of an action, and had to decide which was not part of that action. Solving that task does not require fine kinematic analyses, but an understanding of whether a particular hand-object interaction would be appropriate to achieve a particular goal. In our task, all videos show a hand successfully lifting an object, and performance thus depends on analysis of kinematics. That SCA6 patients were impaired in the Sleeve condition, in which kinematics was the primary cue, but could benefit from additional muscle shape, highlights that cerebellar degeneration particularly impairs kinematic processing. Moreover, these findings dovetail with our functional MRI results, which show consistent cerebellar activity for the kinematic stimuli (Sleeve), but not for the additional shape information provided in the NoSleeve condition. Future experiments comparing performance in action perception and non-biological motion analysis will be needed to explore whether these processes rely on partially distinct cerebellar substrates, or whether the action observation deficit we observed is part of a more general visual motion deficit (Nawrot and Rizzo, 1995; Handel *et al.*, 2009; Avanzino *et al.*, 2015; Broersen *et al.*, 2016).

As the cerebellum is involved in eye movement control, we were concerned that patients may be compromised in their ability to follow the movements of the arm with their gaze. However, our control data obtained from a small number of SCA6 patients do not suggest severe impairments in how our patients deploy their gaze. Future studies could include functional MRI of SCA6 patients to explore where in the cerebellum degeneration alters task-related activity, and whether this includes regions associated with gaze-control. A previous voxel-based morphometry study points to a loss of grey matter in the hemispheres of lobule VI as the primary cause of upper limb ataxia triggered by SCA6 (Rentiya *et al.*, 2017), which is in close vicinity to and partly overlaps with regions in which we found cerebellar activations to action observation, but is lateral relative to the sections of lobule VI mostly associated with eye movements (Supplementary Fig. 5). Data from an additional control experiment further suggest that the differential cerebellar activity is unlikely to be due to differential eye movements (Supplementary Fig. 6).

Based on functional MRI data alone, in 2009 we hypothesized the ventral premotor cortex (vPM), SI and parietal region PF could, via the cerebellum, map visual input, from high level visual regions, onto the motor machinery involved in performing similar actions (Gazzola and Keysers, 2009). Beyond confirming the visual activation of these regions (Supplementary Fig. 7 and Supplementary Table 5), and more finely localizing cerebellar activity, we now show that disorders affecting the cerebellum disrupt action perception as measured by weight judgement. The same task is also disrupted by altering activity in the vPM (Pobric and Hamilton, 2006) or SI (Valchev *et al.*, 2017). Measuring brain activity while perturbing SI, we showed altering activity in one of these nodes disrupts activity of all of those nodes (Valchev *et al.*, 2016)—including the cerebellar lobule VI (Table 2 in Valchev *et al.*, 2016). This suggests that much like action control (Wolpert and Ghahramani, 2000), action observation relies on a cortico-cerebellar loop that maps sensory input onto motor control structures (inverse models) and motor programs to expected sensory input (forward models). This loop brings descending information from our cortical network (includinf vPM, SI, PF, and inferior frontal gyrus/middle temporal gyrus) to the cerebellum

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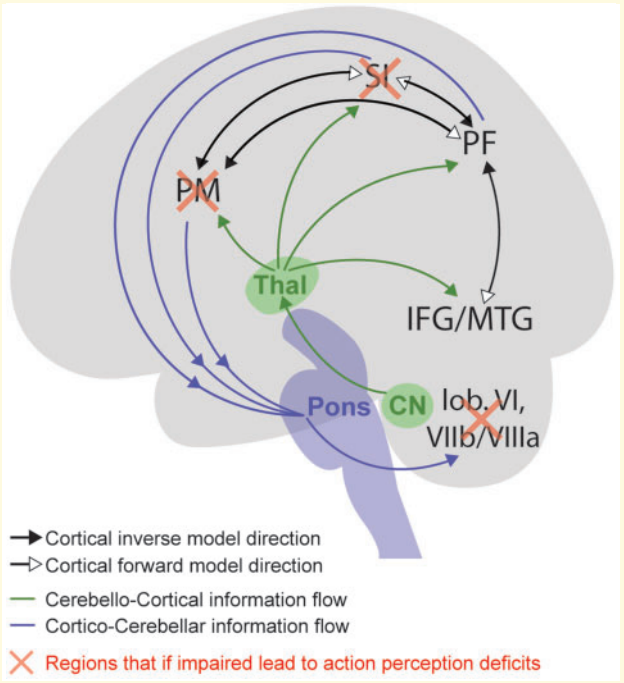

Figure 5 Information flow during action observation. Circuit we propose to be involved in the perception of other people's actions. Cortical regions send information to the cerebellum through the pons (blue arrows), and information processed in the cerebellum flows to the cortex through the thalamus (Thal) via the cerebellar nuclei (CN, green arrows). The different colours of the arrows between cortical regions indicate the direction of the forward and inverse model. Red crosses indicate that a perturbation of the activity in those regions (either by non-invasive brain stimulation technique or degenerative deficits) influences action perception. IFG = inferior frontal gyrus; MTG = middle temporal gyrus; PF = parietal region PF; PM = premotor cortex.

(lobules VI and VIIb/VIIIa) and ascending information from the cerebellum back to the cerebral cortex (Fig. 5). Anatomical studies suggest the former occurs via the pons and the latter via the thalamus and interposed nucleus of the cerebellum (Teune *et al.*, 2000). In line with the latter, we also found robust thalamic activity (Supplementary Fig. 8). Given the strong involvement of all these structures in kinematics rather than shape (Schmahmann and Pandya, 1993), we propose that this loop transforms subtle kinematic cues into reportable perceptions of observed actions. Asking what each brain region individually contributes to this perception/action loop is perhaps as ill posed as asking what each part of a gear-box contributes to torque conversion—function emerges from the interplay of parts. Our Sleeve–NoSleeve data additionally suggest when perception can draw from shape cues, ventral visual brain structures around the fusiform gyrus additionally come into play, but studies investigating the causal impact of these regions onto tasks such as weight discrimination are, to our knowledge, still lacking.

In the light of our findings we believe that it is time to consider the cerebellum a reliable and necessary component of the network that allows us to process the kinematics of observed hand actions. Clinically, one of the core complaints of many stroke survivors and their spouses are impairments in social cognition (Hillis, 2014). These social sequelae are often not on the radar of neurological staff. We hope that by showing that SCA6 patients have deficits in perceiving the kinematics of the actions performed by other individuals—deficits that gets worse with the severity of the disease—our results contribute to an increased awareness that neurological disorders affecting the cerebellum could have consequences for social perception. Being impaired in perceiving what other individuals around us do is likely to impact the way we relate to others and thereby reduce our wellbeing.

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Competing interests

The authors declare no competing interests.

Supplementary material

Supplementary material is available at *Brain* online.

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