Source analyses of axial and vestibular evoked potentials associated with brainstem-spinal reflexes show cerebellar and cortical contributions.

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Highlights:

- Short latency potentials were evoked over the posterior fossa with vestibular and axial stimuli

- Source analysis showed potentials arose predominantly from within the cerebellum and medial forebrain

- Cerebellar excitability changes preceded soleus EMG by approximately 45 ms

- Medial forebrain activations may facilitate subsequent voluntary responses

ABSTRACT

In this work we examine the possible neural basis for two brainstem-spinal reflexes using source analyses of brain activity recorded over the cortex and posterior fossa. In a sample of 5 healthy adult subjects, using axial and vestibular stimulation by means of applied impulsive forces, evoked potentials were recorded with 63 channels using a 10% cerebellar extension montage. In parallel, EMG was recorded from soleus and tibialis anterior muscles and accelerometry from the lower leg. Recordings over the cerebellum (ECeG) confirmed the presence of short latency (SL) potentials and these were associated with changes in high-frequency power. The SL responses to the two stimulus modalities differed in that the axial stimulation produced an initial pause and then a burst in the high-frequency ECeG, followed by excitation/inhibition in soleus while vestibular stimulation produced an initial burst then a pause, followed by inhibition/excitation in soleus. These short latency responses were followed by longer latency N1/P2/N2 responses in the averaged EEG, which were maximal at FCz. Brain Electrical Source Analysis (BESA) demonstrated both cerebellar and cerebral cortical contributions to the short-latency responses and primarily frontal cortex contributions to the long-latency EPs. The latency and polarity of the SL EPs, in conjunction with changes in high-frequency spontaneous activity, are consistent with cerebellar involvement in the control of brainstem-spinal reflexes. The early involvement of frontal cortex and subsequent later activity may be an indicator of the activation of the cortical motor-related system for rapid responses which may follow the reflexive components. These findings provide evidence of the feasibility of non-invasive electrophysiology of the human cerebellum and have demonstrated cerebellar and frontal activations associated with postural-related stimuli.

1. INTRODUCTION

Knowledge of the electrophysiology of the human cerebellum is very limited, despite its potential importance. The cerebellum has its own intrinsic rhythms (electrocerebellogram, ECeG) which have a higher frequency content than cortical EEG [1-2]. Delal et al. [3] summarised the limited observations available on the human electrocerebellogram, noting "the electrophysiology of the human cerebellum remains largely unexplored". They point out that the posterior cerebellar cortex is at a similar depth as the occipital cortex from which EEG (and evoked potentials) are easily measured. Delal et al [3] were aware of only 2 scalp EEG recordings of cerebellar activity. Reports of evoked responses are equally rare, despite there being clear evidence of short latency afferent input from the limbs [4]. There is one report using evoked responses from over the cerebellum during intraoperative monitoring [5]. These authors reported a small N33-P40 response to tibial nerve stimulation with recordings made over the posterior scalp with similar waveforms from electrodes placed over the cerebellum.

We have investigated central vestibular projections by means of evoked potentials. We have used the same acoustic and inertial activations of the vestibular end-organs that produce vestibular evoked myogenic potentials (VEMPs), which in turn are manifestations of vestibular reflex pathways. Using high-density EEG recordings and applying brain electrical source analysis (BESA) methods, we have been able to show the origins of these potentials include cerebellar sources [6-8]. Most recently using the above methods, we provided evidence that short-latency (SL) potentials of likely cerebellar origin co-occur with the VEMPs [9], hence we use the term vestibular cerebellar evoked potentials (or VsCEPs). In the course of this work, we also discovered that it is possible to record the spontaneous activity of the cerebellum, the ECeG) [10], which like VsCEPs can be modulated by stimulus input and context. Both VsCEPs and the ECeG show plasticity and context dependency, typical characteristics of the cerebellum and learning and adaptive timing mechanisms [11].

In the present article we have investigated VsCEPs and the ECeG in combination with a novel extension of the 10-10 electrode placement system over the posterior fossa. Our aim was to provide further detail and resolution on the nature of cerebellar evoked potentials (CEPs) associated with postural reflexes. We were interested to explore the possibility of recording CEPs associated with another putative brainstem-dependent postural reflex, in addition to those produced by vestibular activation. We, therefore, also investigated CEPs produced by axial acceleration which has been established to produce well-defined SL spinal reflexes. This reflex is hypothesized to be mediated through the brainstem and to descend

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92 through the reticulo-spinal system [7-9]. Preliminary investigations suggested this stimulus

93 too was associated with a clear SL CEP. Our principal approach was the use of source

94 analysis of the EEG/ECeG with the aim of comparing the sites of generation within the

95 cerebellum. In conjunction with this we undertook a spectral power analysis of the ECeG.

96

2. MATERIALS AND METHODS

2.1 Subjects

99   Five adult healthy subjects (4 males and 1 female) were recruited from staff at the

100 Prince of Wales Hospital and Western Sydney University. All subjects gave written informed

101 consent before experimentation and the study was approved by the local ethics committee.

102 The work described has been carried out in accordance with the Declaration of Helsinki.

103

2.2 Stimuli

105   Vestibular and axial stimuli were delivered using a hand-held mini-shaker (model

106 4810, Brüel & Kjaer P/L, Denmark) with an acrylic rod attached. The stimulus waveform

107 was a 3rd order gamma function with a 4 ms rise time [15], chosen as an impulsive waveform

108 with a smooth onset. Customized software was used to generate the waveform using a

109 Power1401 (CED, UK) and fed to a power amplifier (model 2718, Brüel & Kjaer P/L,

110 Denmark). The intensity was 20 V peak, equivalent to approximately 14N peak force level

111 (FL). For the vestibular stimulus, the mini-shaker was applied to the left mastoid of all

112 subjects using a positive phase polarity (i.e. initial movement of the acrylic rod was towards

113 the head). This has shown to be an effective vestibular stimulus, capable of evoking postural

114 responses in the legs [16,17]. For the axial stimulus the mini-shaker was applied to the

115 spinous process of the C7 vertebra during anterior lean [13].

116

2.3 EEG/ECeG recording

118   63 channels of EEG/ECeG were recorded from over the scalp and neck using a novel

119 10% cerebellar-extended 10-10 system cap (made to our custom design by EASYCAP

120 GmbH, Germany). The cerebellar extension was designed by completing the population of

121 the Iz row, labelled using the standard nomenclature, from P9 to P10, and adding two

122 additional 10% rows inferiorly, from P11 to P12 and from P13 to P14. Subsequent to the cap

123 design, Heine et al. [18] published an extended electrode placement nomenclature which we

124 have adopted here. The electrodes were of Ag/AgCl type and maintained at 10 kOhms or

125 less. A ground electrode was placed at AFz with reference at Nz. Signals were amplified

using a combination of amplifiers, a 32-channel ActiChamp and a 32-channel Digitimer D360/D120 (Digitimer Co, UK), filtered at 0.5 Hz to 3 kHz and sampled at 10 kHz. The 32 ActiChamp channels were recorded using BrainVision software (version 1.22, Brain Products GmbH, Germany) and the 32 Digitimer amplified channels were sampled using a CED power 1401 and recorded using Signal software (version 6.02, Cambridge Electronic Design, UK). Evoked potential peaks were named based upon their polarity and latency.

2.4 EMG and accelerometry recording.

In parallel with the EEG/ECeG, EMG recordings were made using adhesive electrodes (Cleartrace 1700-030, Conmed Corp., USA) placed bilaterally over the soleus and tibialis anterior (TA) muscles. Active electrodes were positioned 1-2 cm above the musculo-tendinous junction for soleus and 1-2 cm lateral to the tibia for TA with reference electrodes 3 cm below the active electrodes. A ground electrode was placed on the right lower leg. EMG signals were amplified (x1000, Medelec AA6 Mark III), band-pass filtered (8 Hz – 1.6 kHz), sampled at 10 kHz using a Micro1401 (CED, UK) and recorded using the Signal software. Uniaxial accelerometers (model 751-100, Endevco, USA) were placed over the tibial tuberosities.

2.5 Experimental procedure

Recordings were made using two stimulus modalities under three timing conditions. We plan to report the effects of timing conditions separately. Recording began 100 ms prior to the first stimulus. The conditions were: *an irregular condition*, in which the stimuli were presented with a random inter-trial interval (800 ms to 1400 ms), with a recording epoch of 700 ms; secondly, *a regular condition*, in which the stimuli were presented in the form of an anapaest ("Three blind mice") rhythm, with inter stimulus intervals of 600 ms and 1200 ms (inter-trial interval 2400 ms) and, thirdly, *an uncertain condition*, where the third beat of the anapaest rhythm was randomly absent on 50% of trials. The second and third conditions used a longer recording epoch of 2100 ms. The stimulus modalities and timing conditions were scheduled pseudo-randomly. The recordings took place with the subjects standing; for the axial stimulation they were asked to lean forward, but look towards the horizon. Between recordings subjects were allowed to rest sitting down. For the irregular condition subjects were asked to count the total number of trials (75 - 80), for the regular condition to count the number of times they heard "Three blind mice" (36 - 40) and for the uncertain condition to count the number of times they heard the complete "Three blind mice" (46-50). Subjects

160 were asked to report the number and this was recorded for the purpose of ensuring that they

161 were attending to the stimuli.

162 The timing of the trials, stimulus delivery and synchronisation of the parallel EEG and

163 EMG recording systems was controlled by custom software driving a second Power1401

164 digital output. The triggers for the stimuli (either one, two or three per trial) were generated

165 from digital outputs with Signal software while recording the 32 EEG channels. Markers for

166 epoch zero point and trial type were also recorded.

167

2.6 Data analysis

169 After recording EEG/ECeG we performed source localization using the whole 63

170 channels, spectral power analyses of selected channels followed by analysis of the EMG and

171 accelerometry recordings.

172

2.6.1 EEG/ECeG

174 All EEG/ECeG recordings were screened for blinks and other artefacts (about 5 –

175 10% trials) and then merged together using the Scan software (version 4.5, Compumedics

176 Ltd, Australia) and BESA software (version 6.1, MEGIS Software GmbH, Germany). For the

177 electrical source analysis the data were averaged across all timing conditions.

178

2.6.2 Brain Electrical Source Analyses (BESA)

180 The standard four-shell ellipsoidal head model was employed with radial thicknesses

181 of 85, 6, 7 and 1 mm for respectively the head, scalp, bone and CSF, with conductivities of

182 0.33, 0.33, 0.0042 and 1.0, respectively. The fitting was carried out using the BESA genetic

183 algorithm with standard parameter settings.

184 A modelling strategy was adopted to run each genetic algorithm fit 10 times to test its

185 reproducibility using different starting points. A series of models increasing complexity,

186 from one up to 10 dipoles, was run on the short latency epoch (7 – 74 ms) for the two

187 modalities, and then again over the whole epoch (7 – 500 ms) for comparison. For the

188 vestibular condition with four sources the cerebellar sources were constrained to be

189 symmetrical, based on our previous report [19]. For the low order models (up to 4 dipoles)

190 the solutions were unique, but for higher order models, the number of differing solutions

191 increased, indicating that there were likely to be a number of smaller contributors to the

192 recorded surface potentials, in addition to the major sources. Here we have used 4- and 10-

193 dipole model solutions (the latter the maximum allowed on degrees of freedom constraints

for 63 channels with 6 degrees of freedom per dipole). For the 10-dipole model, run 10 times, the resultant 100 locations were then subject to a hierarchical cluster analysis, using the between-groups linkage method with squared Euclidian distance measure, in order to eliminate the non-viable and very weak sources. The 10 runs were repeated for both the short and whole epochs for both stimulus modalities, giving a total of 400 dipole locations. A 5 mm^3 standard deviation was imposed on the cluster volumes and any isolated single dipole sources which resulted from that constraint were eliminated. In addition to the mean Talairach-Tournoux coordinates of the final surviving clusters, a weight was attributed to the clusters derived from the number of dipoles making up the cluster divided by 10 (runs). Thus if the same source appeared for every run its weight would be 1.0.

For cerebellar coordinates the Schmahmann et al. [20] atlas was used to determine the anatomical locations, while for other locations the Talairach Client application (talairach.org, version 2.4.3) was employed with a +/- 5mm^3 search.

2.6.3 Spectral power analyses of spontaneous cerebellar activity

In order to measure any high-frequency pausing or bursting, characteristic of post-climbing fibre responses, a spectral power analysis was also conducted on electrode sites at which the CEPs were most clearly recorded on the scalp (Iz for the axial, PO10 for the vestibular).This used the continuous wavelet transform (CWT) as implemented in the MATLAB toolbox (R2019b, Mathworks, Natick, CA). In the present analysis a Morlet wavelet was employed at a density of 24 voices per octave over 9 octaves. In order to ensure conservation of energy a correction of factor $\sqrt{\frac{10}{f}}$ was applied to match the Fourier equivalent. The CWTs were further transformed to scaleograms (time-frequency images) from the absolute value of the CWT and rescaled to be in dB per Hz re 1 μV^2. Scaleograms were computed for all trials, then further split into six frequency bands; alpha (α: 7.5-12.5 Hz), beta (β: 13-30 Hz), gamma (γ: 30-80 Hz), ultra-gamma (u-γ: 80-160 Hz), very high frequency (VHF: 160-320 Hz) and ultra-high frequency (UHF: 320-640 Hz). These were then averaged to create a grand mean with 700 ms epoch. We also extracted the VHF power at the PO10 (vestibular stimulation) and Iz (axial) electrodes by digital filtering and then RMS (root mean square) averaging. We measured the size of the burst and following pause to correlate these changes with the initial EMG changes in soleus. Burst and pause activity were normalised to the baseline.

2.6.4 EMG/Accelerometry

For each subject and timing condition, averaged RMS recordings of EMG and EEG were used to quantify the evoked reflexes. Acceleration measurements were made for the onset latency and the initial peak for amplitude. For the EMG and accelerometry data, an ANOVA was conducted using modality (vestibular versus axial stimulation), condition (irregular, regular and uncertain) and side (right and left) as factors. Pearson's correlations were used to compare evoked neural responses and soleus EMG for amplitude, with $P < 0.01$ used as the threshold of significance due to the number of comparisons. EMG amplitudes were normalised to the baseline.

3. RESULTS

3.1 Grand means of EEG/ECeG

FIGURES 1 AND 2 HERE

Figures 1 and 2 show the CEP grand means for the axial and vestibular stimuli respectively. Axial stimulation produced a complex sequence of SL waves consisting of P13/N19/P25/N32/P50/N62 peaks at Iz (inverted at Bz). This sequence of waves was mostly sagittally oriented (Figure 1B). For the vestibular case, SL waves consisted of P12/N17 peaks best observed at PO10, contralateral to the side of stimulation, consistent with previous observations [19]. The potential maps showed this dipole was strongly lateralized (Figure 2B). We also identified additional SL waves for the vestibular case, N25/P40/N53 peaks, which were prominent at Bz. In both cases, long-latency (LL) waves were present over frontal electrodes, most prominently at FCz, which we label N1/P2/N2 by analogy to the auditory LL potentials.

3.2 Latencies and amplitudes of the SL and LL EPs.

TABLE I HERE

Table 1 provides mean amplitude and latencies of the early SL EPs (recorded over the posterior scalp) versus LL EPs (recorded at FCz) for the three timing conditions, averaged across trials and for both modalities. For the first two SL waves (axial P13/N19 vs vestibular P12/N17), an ANOVA of the latencies (Table II) indicated only the expected main effect of

"wave". There was a tendency for earlier vestibular wave peaks than their axial counterparts (by about 0.5 ms and 1.8 ms respectively) but this did not reach statistical significance. For the SL amplitudes there was no main effect of wave but there was a main effect of "modality", with the vestibular amplitudes being significantly larger than for the axial stimulus. There was also a two-way interaction between "wave" and "modality": whereas for the axial stimulus the second wave was dominant, for the vestibular case the first wave was larger. Neither latencies nor amplitudes showed an effect of timing condition.

TABLE II HERE

When an ANOVA was carried out for the LL waves a different pattern emerged: There were no significant effects of "modality" and, unlike the case for the SL waves, there was an effect of timing condition on the amplitude. Specifically, lower amplitudes occurred during the regular condition compared to the irregular and uncertain conditions. The amplitudes and latencies both showed a main effect of "wave", the P2 being larger than the N1 and N2 and their having different latencies.

3.3 Source analyses of the vestibular and axial grand means.

FIGURE 3 HERE.

Figure 3 illustrates the structure of global field power for the grands means of the axial (Figure 3A) and vestibular (Figure 3B) stimuli. Both modalities showed a series of short latency lobes, which correspond to the waves identified above. These were followed by three lobes of long latency corresponding to the LL waves N1/P2/N2, where for both stimuli the P2 lobe was dominant. A vertical line at 74 ms marks the approximate division between the short and long epochs.

FIGURE 4 HERE

For the whole epoch, fitting up to four dipoles produced the same solution across the repeated runs (i.e. four narrow clusters with weight = 1.0). Figure 4A & 4C illustrates the 4-dipole solutions showing two cerebellar and two fronto-central sources for both modalities. For the axial case (residual variance (RV) = 12%), the principal cerebellar source (Source 4:

Sc4) was close to the vermis in the posterior lobe. For the vestibular case (RV = 22%), the cerebellar sources were more lateralised (and symmetrical, as imposed). The fronto-central dipoles (Sc1 and Sc2) were similarly located in both modalities, indicating central and anterior cingulate sources. Source currents (Figure 4B & 4D) showed that, for both modalities, the cortical sources (Sc3 and Sc4) were strongly activated within the initial epoch as well as during the later phase.

TABLES III AND IV HERE

For the 10-dipole model runs, the outcomes using hierarchical clustering are shown in Tables III and IV. For the axial case, clustering resulted in 16 whole (w) and 15 short (s) epoch clusters. For the vestibular case, clustering resulted in 15 whole (w) and 14 short (s) epoch clusters. A notable difference between the effects of the two stimuli is the relative contribution of cortical sources. For vestibular stimulation the cortical contribution was largely confined to dorsal mid-line frontal sources. In contrast, for axial stimulation, the cortical contribution was much more widespread, including ventral cingulate and prefrontal cortex, along with parietal, temporal and occipital sources. Both modalities showed bilateral cerebellar and brainstem activity. For axial stimulation, bilateral vermal lobules IX (tonsil) were strongly activated, along with a more lateralised activation of H VIIB/crus II in the right inferior semi-lunaris lobule. For vestibular stimulation, bilateral activation extended to H VIIIA/B of the dorsal paraflocculus. In addition, both stimuli produced sources located outside the brain – from around the eyes and right neck for vestibular simulation, and bilateral neck for the axial stimulation. These were strongly weighted for the vestibular stimulus and presumably represent VEMPs.

3.4 Spectral power of the cerebellar spontaneous activity and its relation to the evoked responses

FIGURE 5 HERE

Figure 5 shows scaleograms of spontaneous cerebellar activity (ECeG) for the two modalities for the irregular timing condition. The power analysis indicated that axial stimulation produced a different pattern of high-frequency pausing from the vestibular stimulus (Fig 5A, B). The effects of axial stimulation consisted of an initial pause followed by a prominent burst associated with the P50 (at Iz: Fig 5D). Vestibular stimulation (Fig 5G)

produced an initial burst of high-frequency power associated with the P12 wave at PO10 (Fig 5J) followed by pausing in the spontaneous activity, especially in the UHF and VHF bands (Fig 5H). Illustrated for comparison are the four-dipole model cerebellar source 3 and 4 currents (Fig 5C, I).

3.5 EMG and accelerometry analyses

Figure 5 (E, K; F, L) illustrates the unrectified leg EMG and RMS averages, along with leg acceleration. Overall, the evoked EMG response was larger for axial stimulation ($F_{(1,44)}$ = 18.0, p < 0.001). Axial stimulation also produced larger accelerations ($F_{(1,37)}$ = 60.1, p <0.001, mean initial peak amplitudes: 6.4 ± 3.9 mg (axial) & 1.7 ± 0.8 mg (vestibular)) and earlier responses ($F_{(2,74)}$ = 37.3, p < 0.001, mean onset latencies: 5.6 ± 1.2 ms (axial) & 14.7 ± 2.7 ms (vestibular)).

The axial stimulus produced bilateral excitatory EMG responses with mean onset and end times of 57.8 ± 3.2 ms and 80.7 ± 5.8 ms respectively, with a mean baseline-corrected amplitude of 27.5 ± 14.9%. In contrast, the vestibular stimulus produced an initially inhibitory response beginning at 55.4 ± 5.8 ms and ending at 92.4 ± 4.4 ms with mean amplitude of 12.3 ± 8.7%. In both cases the EMG onset was preceded by CEPs and associated changes in high-frequency activity. For vestibular stimulation the latency between the onset of the large initial burst associated with the P12 potential and the onset of EMG inhibition was about 48 ms. For axial stimulation, the latency between the onset of the smaller initial pause associated with the P13, to the onset of EMG excitation was about 46 ms, while the latency between the onset of the axially-evoked P50 and associated burst and the onset of EMG inhibition was about 44 ms.

For axial stimulation, the peak to peak P13-N19 amplitudes were significantly correlated with the degree of excitation evoked in soleus ($r_{(26)}$ = 0.66, p < 0.001). There was no such correlation for the vestibular CEPs. For the vestibular stimulus, the size of the VHF burst strongly correlated with the initial inhibitory change in soleus ($r_{(26)}$ = 0.64, p < 0.001), whereas for the axial stimulus there was a trend between the VHF pause and initial excitatory change in soleus ($r_{(26)}$ = 0.34, p = 0.07).

4. DISCUSSION

362   Our present findings confirm the value of recording over the posterior fossa and
363   below and this was made possible with the use of an extended EEG/ECeG cap. We found
364   short latency EPs in posterior electrodes which localised to the cerebellum followed by long-
365   latency EPs in fronto-central leads in response to two distinct stimulus modalities, axial and
366   vestibular. The findings for our vestibular stimulus confirm and extend our previous report of
367   vestibular-evoked cerebellar potentials [11,19,21]. The P12-N17 response in the present
368   study was maximal over PO10, which corresponds to Iz_{+6} in the Govender et al. [19] study.
369   Source analysis, both the 4- and 10-dipole models, showed strong sources bilaterally in the
370   cerebellum, principally in lobules VIIIA and VIIIB. Power analysis confirmed a pause in
371   background activity following the P12 potential, corresponding to the slow wave and this was
372   clearest for the UHF and VHF frequency bands. Source modelling also revealed additional
373   strong sources, for short and long latencies, within the cingulate gyrus, and activity was
374   shown at electrode FCz. The cortical/subcortical sources varied between the two stimuli with
375   the axial stimulus evoking more cortical foci, and both caused activation in the cerebellum.

376   Impulsive stimuli applied to the lower neck, "axial stimuli", have been shown to
377   evoke postural reflexes. The afferent limb does not depend upon vestibular afferents [12,13]
378   and the reflex has been proposed to be a spino-bulbo-spinal one [22]. Like the vestibular
379   stimulus, the axial stimulus evoked robust regions of excitation within the cerebellum and the
380   medial forebrain. For the cerebellum, the most heavily weighted foci lay more medially and
381   were reflected in the recordings at Iz while FCz showed the frontal activations. In contrast to
382   the vestibular stimulus, the initial excitability changes for the ECeG were inhibitory rather
383   than excitatory. Both the vestibular and the axial stimuli are known to evoke postural
384   reflexes. For the vestibular stimulus, the effect on leg muscles is dependent upon head
385   orientation [23] and with the head straight, as here, only a small response in soleus would be
386   expected. In our case, responses were recorded in soleus which were initially excitatory for
387   the axial stimulus but inhibitory for the vestibular one. Corresponding to this and preceding
388   it by 43-45 ms, there were opposite changes in cerebellar excitability. The latency difference
389   is also consistent with previous observations of the likely descending conduction times
390   including the peripheral latency [22]. In the case of the axial stimulus, there was a correlation
391   between the size of the P13-N19 evoked response and the size of the following soleus EMG
392   excitation. For the vestibular stimulus, the VHF power changes showed a correlation
393   between the burst of cerebellar activity and the inhibition in soleus.

394   Previous studies investigating the effects of cerebellar disease on postural reflexes
395   have reported normal latencies but abnormalities in the scaling of responses, with larger and

more variable responses which fail to adapt in response to prior experience [24, 25]. Cerebellar cortical output is solely via Purkinje neurones which are purely inhibitory to their cerebellar nuclear targets. The fastigial nucleus is the most important of these for posture and projects to the medial reticular descending pathways [26, 27]. Eccles et al. [28] showed monosynaptic input from fastigial nuclear neurons to reticulospinal neurones projecting to both the upper and lower limbs. The effects of cerebellar disease and the excitability changes we have found are both consistent with a modulatory role for cerebellar output on postural reflexes and specifically on the brainstem-spinal postural reflexes that we have investigated here.

The second major area of activation (sources 1 and 2, electrode FCz) was located on the medial aspect of the hemispheres in the anterior and middle cingulate gyri. Watson et al. [29] showed that electrical stimulation of the fastigial nucleus, the main output target for the vermis and the nucleus most likely to be activated by our stimuli [27,30], evoked short latency activation of perilimbic, M2 and cingulate areas. They speculated this input could provide relevant proprioceptive information for higher order decision-making processes. Here it may be relevant to note that the axial stimulus which we used needs only to be made slightly stronger and longer in duration, for the reflex response to be followed by a powerful and prolonged voluntary response required to remain upright [31]. The response on the medial aspect of the hemispheres may have a role in mediating the rapid engagement of voluntary pathways when required by a perturbation to stance.

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FIGURE CAPTIONS

Figure 1. (A) CEP grand means for the axial (C7) stimuli averaged across timing conditions. The scalp potential map demonstrates a series of short latency waveforms, centered around Iz. Over the cerebellar electrodes, potentials consisted of a series of waves (P13/N19/P25/N32/P50/N62). Over the frontal electrodes, longer latency N1/P2/N2 waves can be observed which are largest at FCz. (B) Potential maps demonstrate the dipole orientated in the midline over the cerebellar electrodes. For illustrative purposes, only a subset of the 63 electrodes is shown. *The AFz waveform reflects the average of recordings from the AF3 and AF4 locations.

Figure 2. (A) CEP grand means for the vestibular stimulus applied to the left side of the head, averaged across timing conditions. The scalp potential map demonstrates a short latency biphasic waveform contralateral to the side of stimulation which is largest over PO10 (P12/N17). Additional short latency peaks (N25/P40/N53) can also be seen at Bz. Similar to axial stimulation, long latency N1/P2/N2 waves were observed frontally. (B) In contrast to axial stimulation, potential maps show the dipole strongly lateralised for vestibular stimulation. For illustrative purposes, only a subset of the 63 electrodes is shown. *The AFz waveform reflects the average of recordings from the AF3 and AF4 locations.

Figure 3. The global field power (GFP) and grand means at FCz and Iz for the axial stimulus (A) and GFP and grand means at FCz and PO10 for the vestibular stimulus (B). Sequences of short and long latency lobes can be seen for both stimuli. The dashed vertical line demarcates the start of the long latency epoch, as defined for source analysis.

Figure 4. BESA source analysis result (4-dipole solutions). Cerebellar and fronto-central locations rendered in an average MRI (A, C) and the corresponding source currents (B, D) for axial (left column) and vestibular (right column) stimulation. In both cases, sources 1 and 2 (Sc1, Sc2) were in the midline frontally and sources 3 and 4 (Sc3, Sc4) lay in the cerebellum.

Figure 5. Scaleograms (parts A & G) showing the changes in spontaneous cerebellar activity for axial and vestibular stimulation using only the irregular condition. Note pause-burst (B) and burst-pause (H) post-stimulus changes in the very (VHF) and ultra-high frequency (UHF)

588 bands. Source currents for the two cerebellar sources using the 4 source models (C & I)

589 correspond with those of the neural evoked responses at Iz (D) and PO10 (J), in particular the

590 larger P12 vestibular and P50 axial waves. RMS EMG recordings showed SL responses in

591 the soleus (SOL) muscles for both modalities which consisted of an excitation-inhibition for

592 axial stimulation (E) and inhibition-excitation for vestibular stimulation (K). For both

593 modalities, SL EMG responses occurred about 45 ms after the onset of the neural response

594 (see text). Responses in tibialis anterior (TA) were either negligible or consisted of cross-talk

595 from the larger soleus response. Note that the tonic level of EMG has been removed (soleus

596 mean 125 µV, TA mean 36.5 µV). Accelerometry traces from over the tibia (F & L) showed

597 larger induced accelerations for the axial stimulus. The darker traces in E and K show the

598 RMS averages, the lighter the unrectified ones. $mg = 10^{-3}$ g

Axial (C7) stimulation

Figure 1

A

15 µV

100 ms

IO1   IO2

Fpz
Fp1   Fp2

AF7   AFz*   AF8
F7   Fz   F8

FT7   FCz N1 N2   FT8
              P2

T7   Cz   T8

TP7   CPz   TP8

P7   Pz   P8

POz
PO7   PO8

Oz

N32
N19   N62
P9   PO9   Iz   PO10   P10
P13
P25   P50

P11   PO11   SIz   PO12   P12

P13   PO13   Bz   PO14   P14

B

P13	N19	P25	N32	P50	N62
0.2 µV / step	0.5 µV / step	0.5 µV / step	0.5 µV / step	1.6 µV / step	0.6 µV / step

Figure 2

Vestibular stimulation

A

B

P12   N17   N25   P40   N53

A Axial (C7) stimulation

B Vestibular stimulation

Figure 4

Axial (C7) stimulation

Vestibular stimulation

A

Saggital   Transverse   Coronal

Contra   Contra   Ipsi   Contra   Ipsi

Sc2

Sc3

Sc4

B

N1   N2   Sc1

P1

Sc2

Sc3

50 nA
100 ms

Sc4

P50

C

Saggital   Transverse   Coronal

Contra   Contra   Ipsi   Contra   Ipsi

Sc1

Sc2

Sc4

D

N1   N2   Sc1

P1

Sc2

Sc3

50 nA
100 ms

Sc4

P12

Figure 5

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Figure 5. **Axial (C7) stimulation** (panels A–F) and **Vestibular stimulation** (panels G–L).

Table 1

TABLE I: Axial and vestibular short and long latency potential latencies (ms) and amplitudes (µV)

AXIAL	P13	N19	N1	P2	N2
Amplitude					
Irregular	11.3 (6.2)	15.0 (2.7)	10.9 (6.1)	16.9 (6.2)	12.4 (4.5)
Regular	7.9 (11.4)	11.3 (8.1)	5.7 (10.6)	15.5 (4.4)	13.1(4.3)
Uncertain (beat present)	9.2 (10.4)	13.9 (7.9)	10.1 (6.2)	16.7 (6.0)	11.1 (4.3)
Uncertain (beat absent)	11.5 (5.9)	13.8 (8.3)	12.8 (5.6)	17.4 (6.7)	11.2 (4.8)
Mean (SD)	9.8 (8.4)	13.5 (6.7)	9.9 (7.3)	16.6 (5.4)	11.9 (4.2)
Latency					
Irregular	13.5 (1.0)	19.1 (3.1)	108.4 (8.1)	178.0 (17.0)	287.4 (32.7)
Regular	13.1 (2.2)	18.4 (2.3)	104.6 (11.1)	174.2 (9.8)	291.0 (34.7)
Uncertain (beat present)	13.0 (2.1)	18.8 (2.0)	106.6 (8.2)	185.8 (17.6)	299.2 (23.6)
Uncertain (beat absent)	12.4 (2.8)	18.8 (1.9)	106.6 (8.4)	181.4 (12.4)	294.6 (12.4)
Mean (SD)	12.8 (2.2)	18.8 (2.2)	106.9 (8.4)	179.8 (14.0)	293.1 (28.0)
VESTIBULAR	P12	N17	N1	P2	N2
Amplitude					
Irregular	26.3 (8.6)	21.8 (10.8)	14.6 (4.6)	18.6 (5.5)	9.4 (8.4)
Regular	28.3 (2.2)	22.4 (11.3)	8.3 (5.2)	15.0 (6.8)	2.4 (8.8)
Uncertain (beat present)	27.1 (4.4)	23.2 (7.1)	12.2 (2.4)	18.1 (5.1)	5.3 (5.4)
Uncertain (beat absent)	28.1 (3.6)	21.2 (11.9)	8.6 (3.8)	18.9 (4.5)	6.9 (6.8)
Mean (SD)	27.4 (5.8)	22.3 (9.8)	10.9 (4.7)	17.6 (5.3)	6.0 (7.4)
Latency					
Irregular	12.1 (1.4)	16.8 (2.1)	104.4 (7.1)	184.2 (19.1)	295.8 (24.3)
Regular	12.1 (0.9)	16.7 (2.8)	107.6 (10.3)	161.8 (7.8)	290.0 (14.4)
Uncertain (beat present)	12.5 (1.4)	16.9 (1.7)	106.4 (11.2)	189.2 (20.0)	286.4 (18.6)
Uncertain (beat absent)	12.4 (1.3)	17.8 (3.3)	109.2 (12.7)	176.0 (22.1)	298.2 (19.5)
Mean (SD)	12.3 (1.2)	17.0 (2.4)	106.9 (9.8)	177.8 (19.7)	292.6 (18.6)

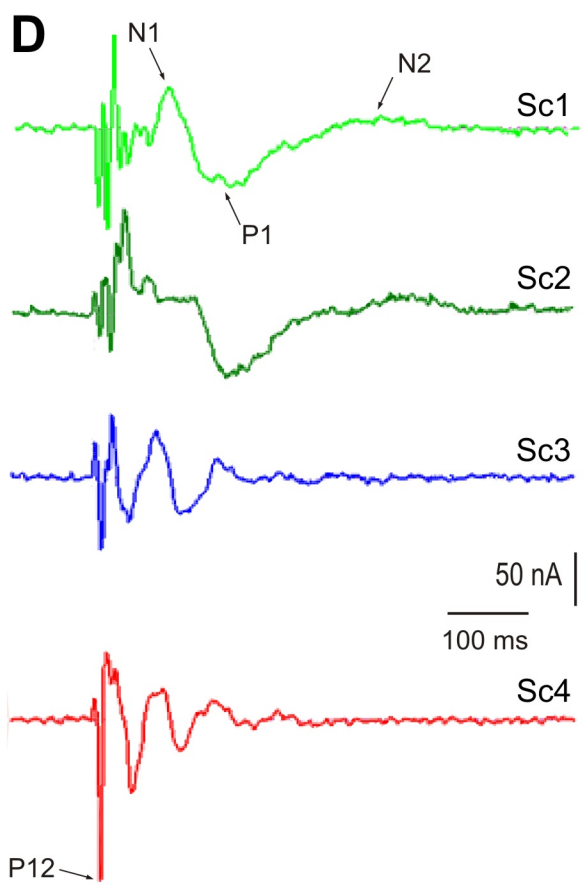Averaged values for all subjects, for all conditions. P13, N19 peaks were recorded at Iz for axial stimulation and P12, N17 peaks were recorded at PO10 for vestibular stimulation. N1, P2 and N2 peaks were recorded at FCz.

Table 2

TABLE II: ANOVA effects for axial and vestibular short and long latency potentials

	Factor	df	Amplitude		Latency	
			F	p	F	p
Short	MOD	1,4	17.7	<.05	1.5	ns
	COND	3,12	0.3	ns	0.2	ns
	WAVE	1,4	0.1	ns	124	<.001
	MOD*COND	3,12	0.8	ns	0.9	ns
	MOD*WAV	1,4	11.7	<.05	2.4	ns
	COND*WAV	3,12	0.7	ns	2.1	ns
	M*C*W	3,12	0.3	ns	0.2	ns
Long	MOD	1,4	0.5	ns	0.1	ns
	COND	3,12	5.3	<.05	2.7	ns
	WAVE	2,8	9.9	<.05	359	<.001
	MOD*COND	3,12	2.2	ns	0.5	ns
	MOD*WAV	2,8	3.9	ns	0.0	ns
	COND*WAV	6,24	1.0	ns	1.9	ns
	M*C*W	6,24	2.1	ns	1.5	ns

Abbreviations: MOD, M – stimulus modality; COND, C – condition; WAV, W – wave, ns- not significant. The latency findings simply confirm the different wave latencies.

Table 3   Click here to access/download;Table;TABLE III.docx ⬇

TABLE III: Summary of BESA results: axial stimulation, 10-dipole model.

Location	Side	Epoch	Brain Area	Weight	X	Y	Z
CEREBRAL CORTEX							
Frontal cortex							
ACG	R	w	24,32	0.8	6	30	14(**Sc1**)
	L	w	24,32,33	0.2	-10	21	17
ReG, MeFG, SuCaG, OrG	L	s	11,25	0.6	-6	21	-19
MeFG, IFG, SuCaG	L	w	25,47,11,10	0.7	-10	27	-14
CG, MeFG	R	s	24,6,31	0.9	5	-3	44
MeFG, Mi FG	L	w,s	6	0.2	-14,17	-15	54,56
Fronto-parietal cortex							
PoCeG, PrCeG	L	s	6,3,4	0.3	-41	-17	64
	R	w	3,4	0.3	26	-27	56
PC L, CG, MeFG, PCun	L+R	w	31,5,6,7	1.5	1	-27	46(**Sc2**)
Temporal cortex							
ITG, MTG	L	s	20,38	0.2	-38	-1	-51
FG, PHG	L	w	37,36	0.6	-43	-37	-7
MTG, STG	R	w	39,22	0.3	48	-51	6
Temporo-parietal cortex							
Insula, STG, IPL	R	w	13,41	0.2	42	-39	18
Parietal cortex							
PCG	L	w	23,30,29	0.4	-9	-57	16
Parieto-occipital cortex							
Cun, PCG	R	s	30,31,18,23	0.2	12	-65	11
Occipital cortex							
MOcG	R	s	18,19	0.3	33	-89	7
SUBCORTEX							
Brainstem							
Pons	L+R	w		0.4	0	-33	-15
Medulla	L	s		0.4	-8	-38	-55
Cerebellum							
Lobule IX (tonsil)	L	s		0.3	-9	-50	-56
	L+R	s,w		1.1,1.0	-1,2	-58,59	-57(**Sc4**)
Lobule V	L	s		0.9	-4	-76	-15
Lobule VIIB	L	w		0.2	-28	-81	-54(**Sc3**)
Crus II	L	w		0.7	-11	-82	-39
Crus II, lobule VIIB	L	s		0.6	-34	-85	-43
Lobule VIIB, crus II	R	s		1.0	31	-85	-52
Crus II	R	w		0.8	25	-86	-37
Neck							
Neck	R	s		0.3	15	-94	-49
	L	w		0.5	-21	-100	-22
	L	s		0.3	-28	-101	-26

Abbreviations: Anterior cingulate gyrus (ACG), cingulate gyrus (CG), cuneus (Cun), inferior frontal gyrus (IFG), inferior parietal lobule (IPL), inferior temporal gyrus (ITG), insula (Ins), fusiform gyrus (FG), medial frontal gyrus (MeFG), middle frontal gyrus (MiFG), middle occipital gyrus (MOcG), middle temporal gyrus (MTG), orbital gyrus (OrG), paracentral lobule (PCL), parahippocampal gyrus (PHG), postcentral gyrus (PoCeG), posterior cingulate gyrus (PCG), precentral gyrus (PrCeG), precuneus (PCun), subcallosal gyrus (SuCaG).

Table 4

TABLE IV: Summary of BESA results: vestibular stimulation, 10-dipole model.

Location	Side	Epoch	Brain Area	Weight	X	Y	Z
CEREBRAL CORTEX							
Frontal cortex							
ACG	L+R	w	24	0.9	0	24	3(**Sc1**)
CG	R	s	32,24	0.3	6	14	33
	R	s	24	0.3	6	-1	39
	L+R	s	24,23	0.6	-1	-10	25(**Sc2**)
	L	w	24,33,31	0.2	-6	-18	37
	R+L	w	31,24,23	0.7	4	-24	37
Me FG, Mi FG, CG,PCL	R	s	6,24,31	0.2	18	-8	52
CG,PCL	L	s	24,31	0.4	-4	-13	40
SUBCORTEX							
Eyes							
Eyes	L+R	w		0.9	-7	71	-33
Basal Ganglia							
Caudate	R	w		0.2	9	17	6
Thalamus							
MDN,Pulv, LDN, VLN	L	w		0.3	9	-20	16
Brainstem							
Pons (within 9mm)	R	s		0.9	6	2	-28
Medulla	R	w		0.8	5	-38	-55
Cerebellum							
Lobule IX (tonsil)	L	s		0.9	-3	-54	-57
Lobule VIIIA	L	s		0.9	-37	-42	-56
Lobule VIIIB	L	w,s		0.6,0.2	-32,27	-46,52	-56(**Sc3**)
	L	s,w		0.2,0.3	-15,21	-62,64	-58
Lobule VIIIA/VIIB	L	w		0.4	-27	-71	-49
	R	w		0.7	31	-72	-53(**Sc4**)
	R	s		0.7	32	-72	-52
Lobule VIIB	L	w		0.7	-36	-74	-58
	L	s		0.7	-38	-73	-58
	L	s		0.9	-28	-82	-47
Crus I/ II	L	w		0.2	-47	-74	-37
Crus I	L	w		0.3	-37	-86	-37
Neck							
Neck	R	w,s		0.9,1.0	26,24	-97,98	-41,38

Abbreviations: Anterior cingulate gyrus (ACG), cingulate gyrus (CG), lateral dorsal nucleus (LDN), medial dorsal nucleus (MDN), medial frontal gyrus (MeFG), middle frontal gyrus (MiFG), pulvinar (Pulv), paracentral lobule (PCL), ventral lateral nucleus (VLN).

Credit Author Statement

All authors contributed significantly to the design of the experiment. Data capture and analysis was primarily conducted by NPT and SG. Drafting of the manuscript was conducted by all authors. Revision of the manuscript was conducted primarily by JC and SG, with inputs from NPT.