Please cite this article in press as: Mochizuki G, et al., Perturbation-evoked cortical activity reflects both the context and consequence of postural instability, Neuroscience (2010), doi: 10.1016/j.neuroscience.2010.07.008

Neuroscience xx (2010) xxx

PERTURBATION-EVOKED CORTICAL ACTIVITY REFLECTS BOTH THE CONTEXT AND CONSEQUENCE OF POSTURAL INSTABILITY

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Abstract—The cerebral cortex may play a role in the control of compensatory balance reactions by optimizing these responses to suit the task conditions and/or to stimulus (i.e. perturbation) characteristics. These possible contributions appear to be reflected by pre-perturbation and post-perturbation cortical activity. While studies have explored the characteristics and possible meaning of these different events (pre- vs. post-) there is little insight into the possible association between them. The purpose of this study was to explore whether pre- and post-perturbation cortical events are associated or whether they reflect different control processes linked to the control of balance. Twelve participants were presented temporally-predictable postural perturbations under four test conditions. The Block/Random tasks were designed to assess modifiability in CNS gain prior to instability, while the Unconstrained/Constrained tasks assessed responsiveness to the magnitude of instability. Perturbations were evoked by releasing a cable which held the participant in a forward lean position. The magnitude of pre-perturbation cortical activity scaled to perturbation amplitude when the magnitude of the perturbation was predictable [$F(3,11)=2.906$, $P<0.05$]. The amplitude of pre-perturbation cortical activity was large when the size of the forthcoming perturbation was unknown (13.8±7.9, 11.4±9.9, 16.9±9.3, and 16.1±10.6 μV for the Block Unconstrained and Constrained and Random Unconstrained and Constrained, respectively). In addition, N1 amplitude scaled to perturbation amplitude regardless of whether the size of the forthcoming perturbation was known (30.1±17.7, 11.4±7.1, 30.9±18.4, 12.4±6.1 μV). This is the first work to examine modifiability in the pre-perturbation cortical activity related to postural set alterations. The cerebral cortex differentially processes independent components prior to and following postural instability to generate compensatory responses linked to the conditions under which instability is experienced.

Key words: evoked potentials, postural set, balance, human.

Compensatory balance responses are essential contributors to one's capacity to prevent falling in the face of postural instability. These responses are generated at short latencies following the onset of instability and scale to the magnitude of instability. Under conditions where the onset or magnitude of instability is unpredictable (such as tripping), the compensatory responses are strongly influenced by the stimulus (Nashner, 1977; Nashner and Cordo, 1981). However, when the characteristics of instability are known (such as self-generated movements or anticipated perturbations), the characteristics of the compensatory responses are modifiable to suit task conditions (Horak et al., 1989). Such modifiability is attributable to alterations in postural set or "state" of the central nervous system (CNS) which occurs in advance of instability and corresponds to expected task conditions (Horak et al., 1989). These alterations occur as a result of past experience or current context; their functional importance in balance control is to optimize the efficiency of compensatory balance responses.

When one considers the factors that contribute to the ability to regulate the gain of the CNS to the expected level of instability, two key factors emerge. The first is the context or the conditions under which the bout of instability is expected to occur. Context is an integral component in set adjustments as internal and external cues provide key information regarding environmental conditions which allows an organism to pre-select the appropriate balance-correcting response (Jacobs and Horak, 2007). The second factor is the consequence or the outcome of instability which is related, in part, to the magnitude of the perturbation. The actual size of instability serves as feedback, allowing for a comparison to be made between a steady state system and a system challenged by instability. Such a comparison provides the CNS with important information for potential future events that may continue to challenge stability. The purpose of the present work is to advance understanding of the association between the pre-perturbation (context-related) and the post-perturbation (consequence-related) cortical activity. Pre-perturbation cortical activity has been suggested to yield insight into the postural set linked to the context of task conditions. However, inferences about postural set have typically come from the examination of the spatiotemporal characteristics of postural responses. These studies have quantified variations

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Abbreviations: ANOVA, analysis of variance; AP, antero-posterior; CNS, central nervous system; COP, centre of pressure; EEG, electroencephalography; EMG, electromyography; EOG, electrooculogram; iEMG, integrated EMG; MG, medial gastrocnemius; TA, tibialis anterior.

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doi:10.1016/j.neuroscience.2010.07.008

in the timing and magnitude of electromyography (EMG) activity in advance of postural instability by varying either the magnitude (in terms of both velocity and amplitude) or direction of instability (Diener et al., 1988; Horak and Diener, 1994). Yet, despite burgeoning evidence to suggest that electroencephalographic measures (EEG) may be illustrative of alterations in postural set, set-based modifications in cortical activity have not been examined with the same vigour. Pre-perturbation cortical activity associated with temporal predictability of destabilizing events have been observed (Jacobs et al., 2008; Maeda and Fujiwara, 2007; Mochizuki et al., 2008; Yoshida et al., 2008) and may be reflective of alterations in postural set. In the aforementioned work measuring cortical activity, the only modification requiring set adjustments was in temporal predictability but not in the magnitude of instability.

Evoked cortical responses occurring after postural instability (N1) have been thought to represent error detection or allocation of cortical resources in response to meaningful stimuli (Adkin et al., 2006). These responses scale to the magnitude of instability (Camilleri et al., 2006; Staines et al., 2001) and are consistently evoked at a fixed latency following the onset of instability (Mochizuki et al., 2009; Quant et al., 2004b). The spatio-temporal profile of these events depicts a system that is sensitive to the size of the error experienced by the system. As noted, N1 has been linked to a cortical marker for error detection, thus the comparison between expected and actual events and the resulting error that occurs may be an important component for evaluating the extent to which measurable cortical events denote processing linked to postural set.

To date, examinations into the contributions of the cortex to balance control have evolved with pre- and post-perturbation cortical events being explored independently. However, given the tight spatial and temporal coupling between events, it is possible that a functionally meaningful relationship exists between the slow-wave shifts that occur prior to perturbation onset and the multi-phasic potentials evoked after the onset of instability. One can envisage a situation in which the detection of the "error" or mobilization of cortical resources in response to a stimulus could be influenced by the underlying level of the CNS at the time at which the error occurred. In contrast, it is possible that pre-perturbation (context) and post-perturbation (consequence) events reflect entirely independent processes. Under such conditions, pre-perturbation cortical activity may be sensitive to the underlying physiological state, where the magnitude of such activity ought to modulate according to the expected magnitude of the perturbation. This activity would have no bearing on post-perturbation responses, which would only be sensitive to the magnitude of the perturbation. Clarifying the relationship between measurable cortical phenomena continues to advance our understanding of the cortical contributions to the control of stability. Assigning functional significance to individual components of cortical events may be valuable in understanding stability control processes in those for whom fall risk is elevated.

No studies have explored whether the amplitude of pre-perturbation cortical activity is related to the expected amplitude of the perturbation. Thus, the first objective was to determine whether pre-perturbation cortical activity scaled to the anticipated amplitude of perturbation. The second objective was to determine whether the amplitude of the pre-perturbation cortical activity and the evoked N1 response were associated. We asked the question: if the initial pre-perturbation activity was larger, linked to the expectation of a large perturbation, would this influence the amplitude of post-perturbation response? This relationship was explored by manipulating the actual and the anticipated amplitude of applied postural perturbation.

EXPERIMENTAL PROCEDURES

Subjects

Twelve subjects (six male, 29.3±6.4 years, 172.1±9.9 cm, 71.6±15.9 kg) agreed to participate in the study. All subjects were free of neuromuscular disorders and each provided written, informed consent prior to the onset of the study. The study was conducted with approval from the Research Ethics Board at the Toronto Rehabilitation Institute.

Data acquisition

Electroencephalography. Electroencephalographic (EEG) signals were obtained using a 32 channel electrode cap (Quik-Cap, Neuroscan, El Paso, TX, USA) based on the International 10–20 System. The impedance for all channels was maintained below 5 kΩ and all channels were referenced to linked mastoids. The electrooculogram (EOG) was obtained using four electrodes, one superior and one inferior to the left eye, and one just lateral to the left and right eye. Electroencephalographic and EOG signals were sampled at 1000 Hz, filtered (DC-300 Hz) online using a NuAmps amplifier (Neuroscan, El Paso, TX, USA) and stored for offline analysis.

Electromyography. Using self-adhering Ag-AgCl electrodes (Meditrace 130; Kendall, Mansfield, MA, USA) with an inter-electrode distance of 20 mm, surface EMG signals were obtained bilaterally from the medial gastrocnemius (MG), tibialis anterior (TA), and upper fibres of the trapezius muscle using a band-pass setting of 10–300 Hz, amplification×2000 and a sampling rate of 1000 Hz (Noraxon, Scottsdale, AZ, USA). Prior to placement of the electrodes, the skin was abraded and cleaned. A single electrode placed on the anterior aspect of the shin just proximal to the ankle joint on the stance leg (see Electromyography in Data Analysis section) served as a ground.

Centre of pressure and pre-perturbation lean force. Centre of pressure (COP) position was monitored prior to and following the perturbation while subjects stood on two adjacent force plates (50 cm long, 25 cm wide; Advanced Mechanical Technology Inc., Watertown, MA, USA) embedded within a raised platform. A third force plate (51 cm long, 46 cm wide, Advanced Mechanical Technology Inc., Watertown, MA, USA) was positioned in front of the subject to capture footfall on trials requiring a stepping response. Centre of pressure position data were sampled at 1000 Hz and collected for 3 s prior to and 2 s after the perturbation. A cable connecting the participant to the platform (Fig. 1) was affixed to an in-line load cell (Transducer Techniques, Temecula, CA, USA), allowing for quantification of the load exerted on the cable resulting from the participant's lean angle prior to perturbation onset. The sharp drop in cable load observed at the time of the perturbation served as the indicator of perturbation onset time. Load cell data was sampled at 1000 Hz and stored for offline analysis.

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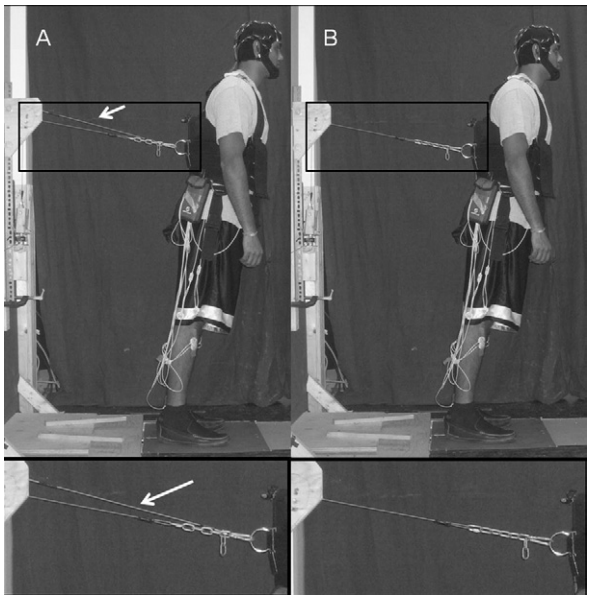

Fig. 1. Experimental set-up for the Constrained (A) and Unconstrained (B) conditions. Inset boxes show the "catch" cable (white arrow) used to decrease the amplitude of postural instability while maintaining the same initial lean angle. Note that the lean angle and foot position was consistent in both task conditions.

Experimental protocol

Predictable, externally-triggered balance perturbations were evoked using a custom-made lean and release cable system. Subjects were attached to the in-line load cell via a lean-control cable positioned over a pulley system that was fastened posteriorly at approximately the level of the 9th thoracic vertebrae to a harness worn by the subject. At the onset of each trial, participants were placed in a standardized foot position using a custom-made template with one foot on each force plate and heel centres 0.17 m apart with a 14° angle between the long axes of the feet (McIlroy and Maki, 1997), with their gaze fixated on a point approximately 3 m ahead of them. Once attached to the cable, subjects were instructed to lean as far forward as the cable would allow, while maintaining full foot contact with the force plates. This position required participants to rotate anteriorly at the ankle joint while keeping the rest of the body segments aligned in a single plane. To ensure consistency across task conditions, the load on the cable, expressed as a percentage of the subject's body weight, was monitored throughout each trial until the time of the perturbation. Additionally, one of the investigators monitored the lower limb EMG signals in the period preceding the perturbation to ensure that there was no preparatory activity. At a point when it was determined that the cable load was appropriate and lower extremity muscle activity was absent, the depression of a mouse button by one of the investigators sent a +5 V pulse to each of the laboratory computers to synchronize data collection and initiate a series of auditory tones (four tones separated by 1 s), with the perturbation occurring in synch with the fourth tone. Perturbations were evoked via manual release of a pin which attached the cable to the load cell. The occurrence of the perturbation was taken as the time at which a decrease of 10.7N was observed (i.e. unloading of the load cell when the pin was removed). Fig. 1 depicts the experimental set-up used in the study.

Task conditions

Postural instability was evoked under four test conditions. In the Unconstrained condition, subjects were attached to the force platform via the load-release cable only. Release of the cable resulted in a large perturbation requiring a stepping response in all trials. In the second task condition, an additional cable was utilized to attach the subject (via the harness) to the frame of the force platform, in-line with the load-release cable. The length of this cable was such that when the subject was leaning as far forward as possible, the load-release cable was taut (i.e. it assumed a similar load as in the Unconstrained condition), while this second cable provided only minimal slack. As such, the initial foot position, lean angle and cable load was kept consistent between conditions. Release of the pin in this Constrained condition resulted in an extremely brief perturbation of small amplitude as the slack in the second cable was taken up rapidly, with the resultant postural reaction most often characterized by a minimal "in place" postural response. Thirty trials of each condition were presented in a blocked order (Block Unconstrained, Block Constrained). Another set of 60 trials was presented in random order (Random Unconstrained, Random Constrained) for a total of 120 trials. A new trial was initiated every 20 s and 5-min breaks were provided between task conditions to prevent fatigue. Prior to each set of trials in the Block conditions, participants were informed about the number and size of the perturbations. Prior to the 60 Random trials, participants were informed that they would experience either a small or large perturbation. In all cases, participants were instructed to "use whatever strategy you need to maintain or regain your balance".

Data analysis

Electroencephalography. Analysis of the EEG data were performed using Scan software (v. 4.3; Neuroscan, El Paso, TX, USA). In synch with the +5 V pulse sent at the onset of the trial, a numeric trigger corresponding to the trial type (i.e. unconstrained or constrained) was placed on the continuous EEG recording. Individual EEG data epochs were derived using this trigger point, with a window of 3500 ms prior to and 500 ms after the trigger. Epochs were then low-pass filtered at 30 Hz and baseline corrected to the average of the first 500 ms of that epoch (−3500 to −3000 ms). Individual epochs were then reviewed and artifacts caused by eye movements were removed from the recordings. Briefly, this process involved identifying the artifact with maximal voltage across all epochs and then constructing an average waveform of any artifacts on an EOG channel that exceeded 15% of the amplitude of the maximal artifact. This waveform was then subtracted from the EEG channel (Mochizuki et al., 2008). Trials corresponding to epochs that were excluded due to artifact were not carried forward for additional analysis (i.e. EEG, EMG and COP). Individual, artifact free epochs were then averaged on the trigger point for each condition within an individual subject, with these files in-turn being averaged across subjects to construct a grand average of the event-related EEG activity associated with each condition.

In order to identify differences in the event-related EEG activity across conditions, the amplitude and latency of pre- and post-perturbation cortical potentials were measured for each individual subject. The onset of pre-perturbation cortical activity was determined using the procedure outlined by Mochizuki and colleagues (2008). Briefly, onset was determined by creating and graphically plotting "bins" of every 50 data points of the averaged waveform for each condition and subject. This plot was then visually inspected to identify the "bin" at which the EEG trace became progressively more negative. The 50 data points contributing to this "bin" were then examined and the onset of pre-perturbation activity defined as the data point at which the EEG trace displayed a more negative value than those preceding it, without a return to more positive values subsequent to it. In a small sub-set of subjects (n=2), the onset of pre-perturbation cortical activity was difficult to discriminate due to the relative absence of this response across all conditions. In these instances, the onset

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of pre-perturbation cortical activity was set as the average onset derived from the other participants.

N1 response latency was determined by marking the time of the negative peak in the 500 ms following the onset of the perturbation (equal to time "0"). Amplitude of the pre-perturbation cortical activity was quantified as the voltage difference between perturbation onset (time "0") and onset of the pre-perturbation activity. N1 response amplitude was quantified as the difference in voltage between perturbation onset and the peak of the N1 response. As previous studies have shown the N1 response magnitude to be greatest at fronto-central electrode sites (Quant et al., 2004b), analysis of the EEG signals was limited to the Cz electrode.

Electromyography. EMG signals were conditioned for analysis by removing any zero-offset bias followed by full-wave rectification of the signal. Onset of the initial EMG burst was defined as the time at which the EMG amplitude exceeded +3 standard deviations greater than the mean of a 1000 ms baseline value (500–1500 ms) taken prior to the perturbation for a period of ≥25 ms. Onset markers were automatically positioned by the software, but were reviewed for accuracy and manually repositioned if required. The magnitude of the EMG response was quantified as the total integrated EMG over a 200 ms window following EMG onset ($iEMG_{200ms}$). Analysis of the EMG data was performed separately for the stepping leg (leg used for compensatory change-in-support response in Unconstrained trials) and the stance leg (leg used to support body weight during change-in-support response).

To investigate the possibility of early anticipatory muscle responses occurring prior to the perturbation, we quantified the magnitude of the pre-perturbation EMG activity in all trials for each subject in two 1000 ms windows (−3000 to −2000 ms and −1000 to 0 ms) to allow for comparison of the activity just preceding the perturbation to a baseline value. Briefly, if EMG activity in the −1000 to 0 ms window exceeded the mean+1 standard deviation of the activity in the −3000 to −2000 ms window, that trial was excluded from all aspects of the data analysis.

Centre of pressure. Anterior-posterior (AP) centre of pressure excursion onset latencies and peak values were determined based on the overall AP-COP waveforms (combination of right and left AP-COP data). The onset of the AP-COP excursion was marked manually as the time at which a positive, sustained increase in slope occurred within a 140 ms window post-perturbation onset. Amplitude of the AP-COP response was calculated as the difference between the peak COP position, defined and marked manually as the maximum value of the COP excursion within a 400 ms window of perturbation onset, and the onset position. Latency of the AP-COP peak was also recorded. Lastly, in an additional effort to control for anticipatory postural responses, data from individual trials were inspected for COP excursions during the 500 ms epoch preceding the onset of perturbation. Consistent with the EMG data analysis, trials in which these COP excursions were present were removed from all aspects of data analysis. Electromyography and COP data analysis were performed using custom-made programs created in the LabVIEW environment (v7.1; National Instruments, Austin, TX, USA).

Statistical analysis

In order to perform a similar analysis of the data across conditions and individual subjects, statistical analyses were performed on values derived from averaging the raw time series data from individual trials. Specifically, the data points for all trials that were included in the data analysis for a given condition were averaged for each participant. The resultant averaged time series data were then analyzed as described above. Prior to statistical analysis, all data were examined using the D'Agostino and Pearson omnibus normality test (D'Agostino, 1986). Although all datasets passed the normality test ($P>0.05$ throughout), a degree of variability was observed about the normal distribution. Accordingly, a square root data transformation was applied to all datasets prior to further analysis. Following this transformation, within-subject comparisons of the effect of condition (Block Unconstrained, Block Constrained, Random Unconstrained, Random Constrained) on EEG (pre-perturbation cortical activity latency and amplitude; N1 peak latency and amplitude), EMG (onset and $iEMG_{200ms}$), and COP measures (onset and amplitude) were performed using a one-way repeated measures analysis of variance. Additionally, the number of trials included post-data analysis across conditions was analyzed using one-way repeated measures analysis of variance (ANOVA). Where applicable, post hoc analyses were performed using Tukey's test of multiple comparisons. Pearson product moment correlation coefficients were calculated to measure the level of association between the amplitudes of pre- and post perturbation cortical potentials. Values presented throughout represent means±standard deviation unless otherwise stated. An a priori alpha level of $P<0.05$ was utilized to denote statistical significance.

RESULTS

Following data analysis and subsequent removal of individual trials due to ocular artifact or anticipatory postural responses, a similar number of trials [$F(3,11)=1.437$, $P>0.05$] per subject for each of the task conditions was included in the statistical analysis (20±4, 20±4, 18±1 and 20±3 Block Unconstrained and Constrained, Random Unconstrained and Constrained respectively). Fig. 2 is a representative depiction of the EEG, EMG, and COP plots for a single participant, averaged across all trials.

Electroencephalography

Grand averaged cortical activity occurring prior to and in response to the predictable postural perturbation across task conditions was characterized by a slow-wave DC potential beginning approximately −1172 ms prior to perturbation onset. On average, the magnitude of this slow-wave pre-perturbation activity across conditions was 14.5 μV. An N1 potential was clearly discernable for each of the task conditions, with an average peak latencies of 98.6 ms after the onset of perturbation. The amplitude of this N1 potential was 21.2 μV averaged across conditions.

Analysis of the pre-perturbation-evoked cortical activity across conditions within individual subjects revealed no significant differences in onset latency [$F(3,11)=0.4186$, $P>0.05$]. Conversely, a significant main effect for task condition on the amplitude of the pre-perturbation slow-wave potentials was observed [$F(3,11)=2.906$, $P<0.05$]. Post hoc analyses revealed a significant difference between the Blocked Constrained and Random Unconstrained conditions only.

Closer inspection of the data revealed a consistent pattern of change within the pre-perturbation slow wave potentials across the four task conditions with the exception of three participants (Fig. 3). Specifically, among these three participants, the amplitude of pre-perturbation cortical activity was smaller in the Block Unconstrained condition than all other conditions, contrary to the results of the majority of participants (Fig. 4). Secondary analysis performed with these data omitted revealed a stronger interaction for task condition on the amplitude of pre-perturba-

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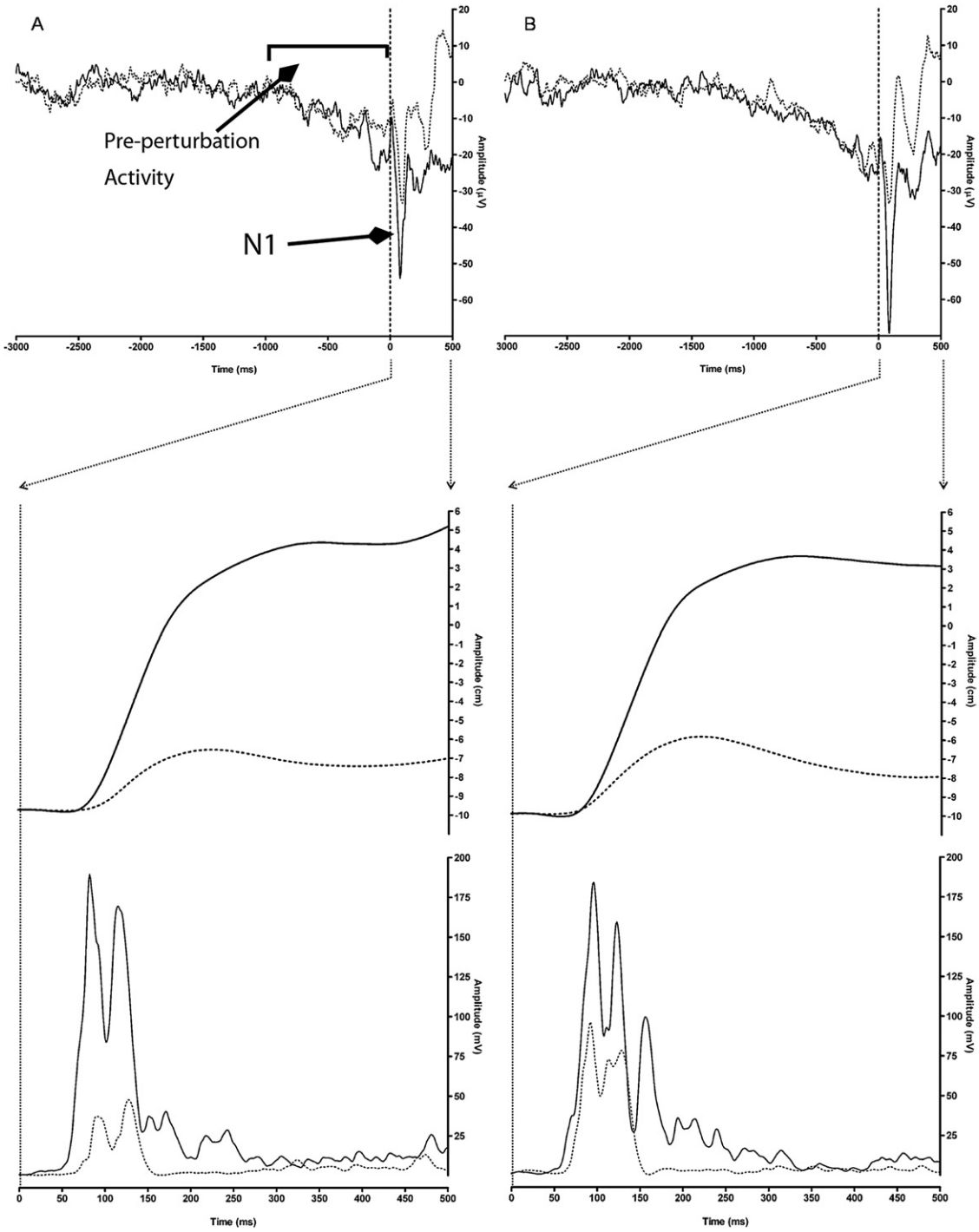

Fig. 2. Single subject representation of the EEG (top panel), COP (middle panel), and stepping limb gastrocnemius EMG (bottom panel) averaged across all trials in the Block (A) and Random (B) conditions. The Unconstrained and Constrained conditions are depicted by the solid and dotted lines, respectively. The vertical dashed line at time=0 represents perturbation onset.

tion cortical activity [$F(3,8)=6.739$, $P<0.05$], with post hoc analyses revealing a significant difference between the Block Constrained and all other task conditions. No other between-condition differences were noted for pre-perturbation cortical activity amplitude. To ensure consistency, we performed this secondary analysis with the data from these three subjects omitted for the remaining EEG indices and both the EMG and COP data. As no differences were detected between the secondary and original analyses for these parameters, the remaining results include data from all 12 participants.

Statistical analysis of the latency of the N1 peak also demonstrated similarities across conditions, with no significant differences observed [$F(3,11)=1.584$, $P>0.05$]. Lastly,

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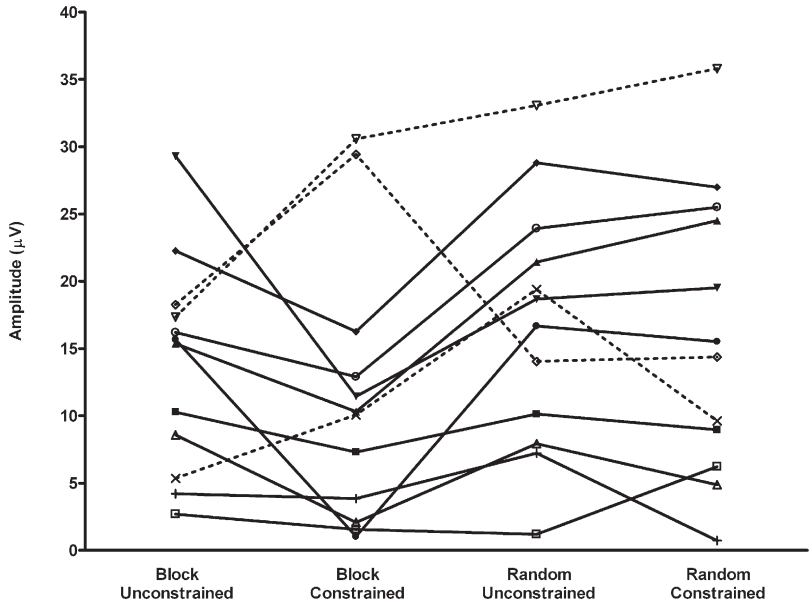

Fig. 3. Amplitude of pre-perturbation cortical activity in each condition for individual participants. Dashed traces represent participants with larger amplitude activity in the Blocked Constrained condition. All other participants demonstrate a reduction in amplitude in the Blocked Constrained relative to the other task conditions.

and comparable to the grand averaged waveforms, a significant main effect was found for N1 potential amplitude across our task conditions [$F(3,11)=21.27$, $P<0.05$]. Specifically, post hoc analyses confirmed a significant difference in N1 amplitude between the Unconstrained conditions (30.1±17.7 and 30.9±18.4 μV, Block and Random Unconstrained, respectively) and the Constrained conditions (11.4±7.1 and 12.4±6.1 μV, Block and Random Constrained, respectively) with no differences observed within either the Unconstrained or Constrained conditions (i.e. Block vs. Random). Table 1 presents the values for all electroencephalographic measures.

In three of the test conditions (Block Unconstrained, Random Unconstrained, Random Constrained), low levels of association were found to exist between the transformed values of the amplitude of pre- and post-perturbation cortical events. Pearson's *r*-values for those conditions were: $r=-0.12$ ($P=0.70$), $r=-0.08$ ($P=0.80$), and $r=0.13$ ($P=0.68$), respectively. The correlation between cortical measures in the Block Constrained was moderate ($r=0.57$,

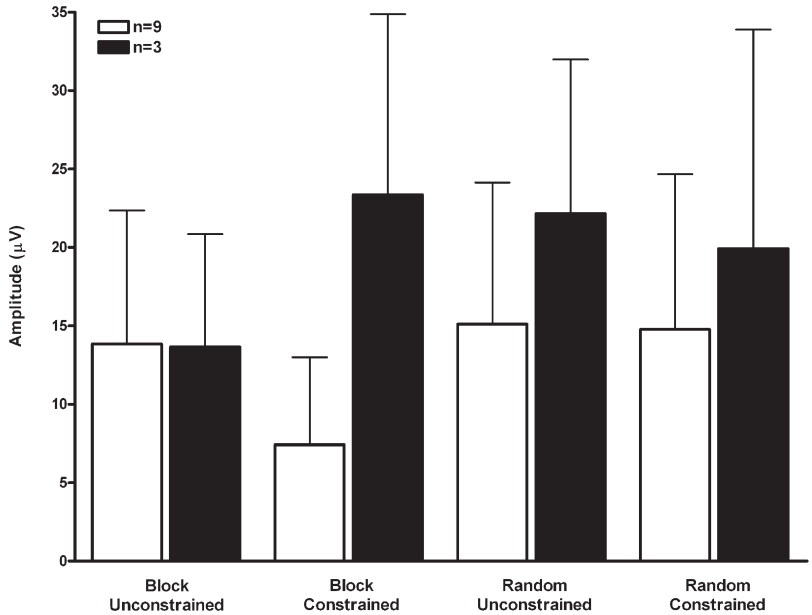

Fig. 4. Pre-perturbation EEG amplitude in the main group of participants (open bars) and those displaying altered patterns of activity (filled bars). Values are presented as mean±standard deviation.

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Table 1. Electroencephalography data across the task conditions

Condition	Electroencephalography (EEG)			
	Pre-perturbation cortical activity		N1	
	Onset (ms)	Amp (μV)	Peak latency (ms)	Amp (μV)
Block unconstrained	−1130±298	13.8±7.9	97.8±11.6	30.1±17.7
Block constrained	−1191±360	11.4±9.9	94.3±14.0	11.4±7.1
Random unconstrained	−1211±224	16.9±9.3	100.6±12.0	30.9±18.4
Random constrained	−1127±193	16.1±10.6	101.9±13.1	12.4±6.1

Measures of pre- and post-perturbation electroencephalographic activity (n=12). Values are presented as mean±standard deviation.

P=0.053). Fig. 5 illustrates the relationship between pre- and post-perturbation cortical events for each task.

Electromyography

Compensatory postural reactions to the perturbation were present in all conditions demonstrated by a rapid onset of MG activation. Onset times of the MG muscle activation did not differ between the task conditions for either the stepping [$F(3,11)$=1.052, P>0.05] or stance leg [$F(3,11)$=1.193, P>0.05, Table 2]. In line with our hypotheses, the magnitude of MG activation differed across conditions, with a main effect observed for condition in both the stepping [$F(3,11)$=27.29, P<0.05] and stance leg [$F(3,11)$=28.32, P<0.05, Table 2]. Post hoc analyses were analogous for the stepping and stance legs, revealing significant differences between the Unconstrained and Constrained conditions in both the Block and Random trials. In addition, there was a significant difference in MG $iEMG_{200ms}$ between the Block and Random Constrained conditions for the stepping leg. No such differences were observed in the Unconstrained conditions.

Centre of pressure and lean force

Analysis of the load exerted on the load-release cable prior to perturbation onset revealed no differences across task conditions [$F(3,11)$=2.519, P>0.05)], with percent body

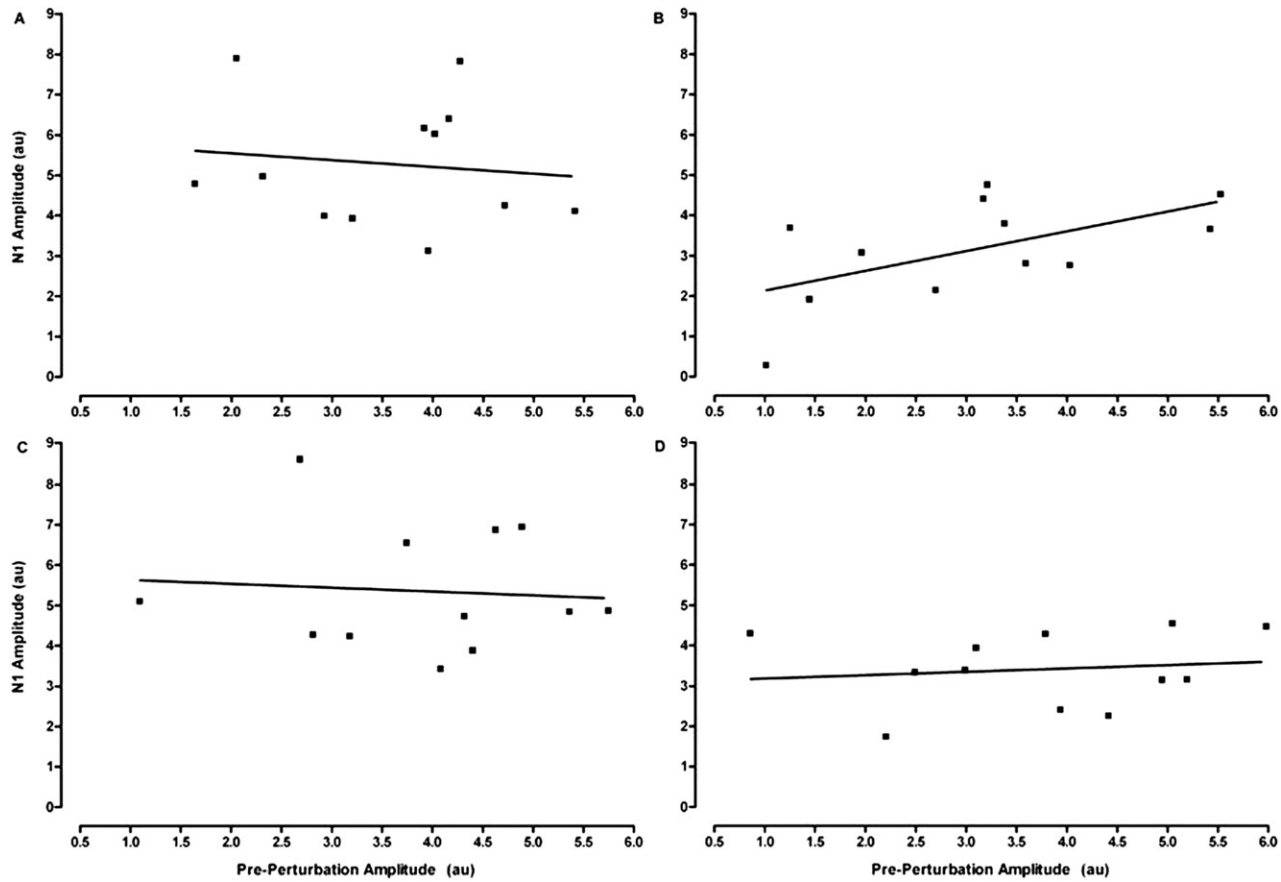

Fig. 5. Scatter plot and trend line depicting the relationship between the log transformed values for pre- and post-perturbation (N1) cortical potential amplitude. (A) Block Unconstrained; (B) Block Constrained; (C) Random Unconstrained; (D) Random Constrained.

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Table 2. Electromyography and centre of pressure data across the task conditions

	Electromyography (EMG)				Centre of pressure (COP)	
	Stepping leg		Stance leg		Onset (ms)	Amplitude (cm)
Condition	Onset (ms)	$iEMG_{200ms}$ (mVms)	Onset (ms)	$iEMG_{200ms}$ (mVms)		
Block unconstrained	55.2±8.1	12.9±9.1	61.0±9.3	13.5±8.3	78.6±14.0	9.3±2.6
Block constrained	58.3±6.1	1.9±1.3	60.3±10.2	2.2±2.5	66.0±18.2	3.3±4.1
Random unconstrained	55.3±8.0	13.7±9.8	60.9±9.4	12.7±7.4	76.7±14.3	11.0±0.9
Random constrained	57.4±5.6	5.2±2.6	55.8±6.2	4.2±2.6	64.5±11.5	5.4±2.3

Measures of electromyography and centre of pressure (n=12). Values are presented as mean±standard deviation.

weight values of 9.6±1.9 (Block Unconstrained), 9.9±1.9 (Block Constrained) and 10.2±1.6% (Random Unconstrained and Constrained). Despite equivalent pre-perturbation conditions, the compensatory response differed considerably between the Unconstrained and the Constrained conditions. Perturbations evoked during the Unconstrained conditions required a stepping response in 100% of the trials performed in the study. This is in sharp contrast to the Constrained conditions, which were most often characterized by a minimal "foot-in-place" response, with a stepping response observed in <0.3% of all trials (2 out of 720 Constrained trials). Further analysis of the compensatory response in the form of the AP-COP excursion revealed a significant main effect for task condition [$F(3,11)=22.07$, $P<0.05$], with larger magnitude COP excursions observed for the Unconstrained compared to the Constrained conditions (Table 2). Post hoc analyses further confirmed that these significant differences existed only across conditions, with no difference observed within either the Unconstrained or Constrained conditions. Lastly, our analysis revealed that the variability noted in AP-COP onset times between conditions was different [$F(3,11)=5.562$, $P<0.05$], with variability noted between the Unconstrained and Constrained conditions for both Block and Random trials (Table 2).

DISCUSSION

This study set out to determine the extent to which alterations in postural set modified the spatio-temporal characteristics of cortical potentials evoked by instability. Specifically, the current study explored the association between pre-perturbation (context) and post-perturbation (consequence) cortical activity associated with perturbations to upright stability. The main findings of this study were: (1) the magnitude of pre-perturbation cortical activity was scaled to perturbation amplitude when the size of the perturbation could be anticipated and (2) there was no association between the amplitude of the pre- and post-perturbation cortical activity when the actual size of the perturbation did not coincide with the anticipated amplitude of perturbation. Specifically, the magnitude of pre-perturbation cortical activity was large when the size of the forthcoming perturbation was unknown; and the magnitude of post-perturbation cortical activity was always scaled to perturbation amplitude regardless of whether the size of the forthcoming perturbation was known or unknown. We believe this reveals important distinctions in the CNS processing linked to postural set and the reactive elements of the cortical activity linked to postural instability. The relationship between pre- and post-perturbation cortical events and their link to adjustments in physiological state are discussed below.

Cortical activity associated with postural set

To our knowledge, this is the first study to demonstrate amplitude modulation in pre-perturbation cortical activity related to changes in the magnitude, rather than the temporal predictability (Jacobs et al., 2008; Mochizuki et al., 2008) of postural instability. In the Random tasks, the amplitude of pre-perturbation cortical signals did not vary and were relatively large in magnitude. Based on these cortical markers, the CNS appears to have a "default" level of set when the magnitude of instability is unpredictable. Functionally, the CNS may alter its set in preparation for a worst-case scenario whereby, in the absence of contextual cues which are indicative of the specific parameters of imminent instability, the most ecologically valid solution is to engage the resources that would be required for responding to the highest level of threat. In the present study, this high threat level was established in the Block Unconstrained condition which served as a baseline level to which current context could be compared.

The hypothesis that the CNS adjusts its gain to a default setting under conditions of unpredictability has been postulated in postural tasks (Beckley et al., 1991) as well as in upper limb reaching movements (Cordo, 1987; Hening et al., 1988). Beckley and colleagues showed that when presented with the possibility of experiencing one of two perturbation amplitudes, the amplitude of the long latency response in tibialis anterior was set to a default mode to the larger of the two possible outcomes. This was in contrast to the findings of Horak et al. (1989), who showed that the default setting was generated anticipating medium-sized perturbations. These discrepancies were attributed to differences in the potential number of perturbation amplitudes between studies (i.e. two in Beckley et al., 1991 and five in Horak et al., 1989). The present study also only presented two options for perturbation amplitude with pre-perturbation cortical activity defaulting to the larger of the two conditions. It is possible that a "medium" default setting could have been demonstrated had more options been presented. However, more important than the abso-

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lute amplitude of cortical activity associated with postural set adjustments was the demonstration that this activity could be modified.

Unexpectedly, three participants demonstrated a pattern of responses in pre-perturbation measures that was in opposition to the experimental hypothesis (Figs. 3 and 4). These participants revealed greater activity in the Block Constrained condition than in the Block Unconstrained condition. One possible explanation for these results is that subjects may have engaged alternate cortical processes in the Block Constrained condition. Some participants reported volitionally preparing for the next trial in the block as the current trial was ongoing. Cortical events related to motor preparation are also characterized by slow-wave negative activity (Kornhuber and Deecke, 1965) and may have manifested in these participants. This is plausible if current context dictated that relatively fewer resources were required in this condition, thus allowing those resources to be diverted elsewhere (i.e. preparation for the next event). Indeed, re-allocation of cortical resources has been shown to modulate the amplitude of perturbation-evoked cortical potentials in a cognitive dual-task paradigm (Quant et al., 2004a).

Post-perturbation responses

The cortical potentials evoked by instability (N1) scaled to the magnitude of instability in both the Block and Random conditions. The method by which perturbations were presented (Block vs. Random) also had no effect on the latency of the N1 peak. These findings are in keeping with previous work demonstrating the sensitivity of the N1 to perturbation amplitude (Camilleri et al., 2006; Staines et al., 2001). It should be noted that in the Constrained condition, there were two distinct stimuli to which participants could have responded: the release and the catch. Given the similarities in timing of the N1 potentials across conditions, it could be speculated that the onset of N1 was indicative of the perception of the release, while the amplitude of the N1 was linked to the catch (i.e. its presence in the Constrained condition or absence in the Unconstrained condition). It is this feature that reflects the "consequence" of instability. Within the context of balance control, current hypotheses link the N1 to error detection or allocation of cortical resources (Adkin et al., 2006). The findings of the current study are consistent with this hypothesis in that the CNS could characterize larger perturbations as being indicative of a larger error to homeostasis or as a larger stimulus to which cortical resources need to be directed.

In addition to cortical measures, analysis of the associated postural responses revealed similar scaling to the magnitude of instability and insensitivity to the way in which the perturbations were grouped. Gastrocnemius integrated EMG (iEMG) scaled to perturbation amplitude, consistent with previous reports for instability in the anterior direction (Diener et al., 1988). The iEMG also scaled with the level of predictability (i.e. Random vs. Block), but only in the Constrained condition. This is consistent with the findings of Burleigh and Horak (1996) who demonstrated scaling of the iEMG taken over the initial 50 ms of the postural response. While the present work did not find such scalability in the iEMG when perturbations were large (i.e. Unconstrained), this feature of the behavioural response was linked to the cortical measures. That is, there were no differences in N1 amplitude between Unconstrained conditions. Within this context, it is possible that the perturbation characteristics, reflected by N1 amplitude, were sufficiently large to override a potential modulatory effect of an adjustment in set. This may also be an illustration of the apparent dissociation between pre- and post-perturbation cortical events.

Pre- and post-cortical events: independence or interaction?

The findings of the current study indicate that cortical activity associated with instability represents distinct cortical processes. Analysis of the level of association between pre- and post-perturbation cortical events revealed only a moderate level of correlation ($r=0.57$) for the Block Constrained condition only. All other correlation values were below $r=0.13$ and statistically non-significant. In the Block conditions, where perturbation magnitude was known by the participant, most participants revealed a pattern of activity whereby pre-perturbation cortical activity scaled to the expected size of instability, while the N1 scaled to the actual size of instability. This link could be interpreted as a process whereby the CNS gain is adequately adjusted to optimize postural responses to instability when the precise characteristics of instability (i.e. timing, direction, magnitude) are known. In contrast, the presentation of stimuli in random order engaged the adjustments in postural set to the same magnitude in each trial, with no additional alterations to either the cortical responses. These responses maintained their sensitivity to the actual magnitude of instability.

The present results indicate that only in instances where both the context and consequence of instability are not perceived as being potentially harmful does the CNS regulate cortical events in unison. Alternatively, these task conditions may depict a scenario where relatively few resources are required for ongoing control, allowing the CNS to operate at a steady state. In other situations, which are more representative of real-world situations, cortical events maintain their specificity. For example, when a greater degree of instability is imminent or when greater instability has the potential of occurring, pre- and post-perturbation cortical events appear to maintain independence.

Few other studies have characterized the cortical events that both precede and follow a perturbation. Though not related to postural instability, some parallels can be drawn between the current work and that of Kourtis et al. (2008) evaluating the cortical events preceding and following load alterations during precision gripping. Temporally predictable perturbations evoked cortical activity prior to the onset of the load perturbation and also muted the amplitude of cortical potentials following the perturbation. It was suggested that this activity mediated the long-latency reflexes evoked by the load perturbation. These find-

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ings are consistent with those related to balance control, indicating that temporal predictability mutes the magnitude of cortical responses to instability (Adkin et al., 2006; Mochizuki et al., 2008). These data suggest that pre-perturbation events do influence cortical activity evoked by the perturbation.

This interpretation must be made with caution, especially when one considers the functional role of alterations in postural set. If the gain of the CNS is altered to optimize postural responses, the question that must be asked is: what evidence is there that this optimization occurred? The gastrocnemius EMG demonstrated differences in magnitude which were dependent upon perturbation amplitude, irrespective of whether the perturbations were blocked or randomly presented. However, EMG amplitude remained muted in the Random Constrained condition, scaling to perturbation amplitude rather than to pre-perturbation EEG amplitude. Coupled with the vast differences in step incidence between the Constrained and Unconstrained tasks ($<$0.3% vs. 100%, respectively), scaling in response amplitude seem to indicate that the responses were optimized to task conditions.

The aforementioned studies indicate that alterations in physiological state reduce the size of the perceived error or requirement for allocation of cortical resources, as indicated by the N1. However, if pre- and post-perturbation cortical events were coupled in this manner, one would expect an inverse relationship between the amplitude of pre- and post-perturbation events. That is, progressively larger pre-perturbation cortical events, demonstrative of set adjustments, ought to result in progressively smaller N1 responses. The current study shows the opposite to be true. This could be interpreted a number of ways. Firstly, it is possible that response specificity to perturbation characteristics is an example of optimization. Cortical events associated with postural responses may have the capacity to scale with greater sensitivity as it incorporates somatosensory feedback in its response (Dietz et al., 1984, 1985). If pre-perturbation events reflect changes in set, then they may incorporate multi-modal processes that are more generalizable (i.e. past experience or context; Jacobs and Horak, 2007) which lack the sensitivity to reflect discrete differences in task conditions. It should also be noted that while perturbation magnitude was varied, the timing of perturbation onset was constant. The similarities in pre-perturbation amplitude observed in the two Random conditions could be reflective of set adjustments specific to timing rather than a default setting for amplitude. In this scenario, the system could be primed to generate specific responses, regardless of the size of instability. It must also be acknowledged that the lean position used in the study was not a position that would readily be experienced in the real-world. And, while the present results provide insight into the contributions of the cortex to balance control (based on pre-perturbation and N1 potentials), owing to the methods in which the perturbations were performed, it remains uncertain whether such contributions would be evident under a more ecologically valid condition (i.e. upright stance). Indeed, the forward lean position in itself is an alteration in context and may generate different patterns of cortical activity compared to what might be observed in upright stance. Future studies should explore the robustness of the independence between pre- and post-perturbation cortical events. While this challenges the generalizability of the results, the specificity of the recorded cortical activity to the context and consequence of instability do advance the understanding of the involvement of the cortex in human postural control.

CONCLUSION

In summary, this study has demonstrated that pre-perturbation cortical activity tends to vary with the anticipated amplitude of perturbation. If the amplitude of imminent instability is unpredictable, the CNS sets a “default” setting to an increase in gain. These characteristics of cortical activity parallel previous observations based on muscle activity and provide additional support for the hypothesis that slow-wave potentials generated in advance of imminent instability are indicators of postural set, specific to the context in which instability is experienced. In contrast, cortical potentials generated following a bout of instability are sensitive only to the specific parameters (i.e. consequence) of instability. This work demonstrates that cortical events associated with pre and post-perturbation aspects of balance control are independent from one another and are specific to the underlying processes involved in maintaining stability.

Acknowledgments—The authors wish to thank H Cheung and R Lee for assistance with data collection. This work is supported by funding from the Heart and Stroke Foundation of Canada (GM, SB), the Canadian Stroke Network (SB), and the Natural Science and Engineering Research Council (WEM). We acknowledge the support of the Toronto Rehabilitation Institute who receives funding under the Provincial Rehabilitation Research Program from the Ministry of Health and Long Term Care in Ontario.

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(Accepted 4 July 2010)

Please cite this article in press as: Mochizuki G, et al., Perturbation-evoked cortical activity reflects both the context and consequence of postural instability, Neuroscience (2010), doi: 10.1016/j.neuroscience.2010.07.008