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The Neuroanatomical Correlates of Training-Related Perceptuo-Reflex Uncoupling in Dancers

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Sensory input evokes low-order reflexes and higher-order perceptual responses. Vestibular stimulation elicits vestibular-ocular reflex (VOR) and self-motion perception (e.g., vertigo) whose response durations are normally equal. Adaptation to repeated whole-body rotations, for example, ballet training, is known to reduce vestibular responses. We investigated the neuroanatomical correlates of vestibular perceptuo-reflex adaptation in ballet dancers and controls. Dancers' vestibular-reflex and perceptual responses to whole-body yaw-plane step rotations were: (1) Briefer and (2) uncorrelated (controls' reflex and perception were correlated). Voxel-based morphometry showed a selective gray matter (GM) reduction in dancers' vestibular cerebellum correlating with ballet experience. Dancers' vestibular cerebellar GM density reduction was related to shorter perceptual responses (i.e. positively correlated) but longer VOR duration (negatively correlated). Contrastingly, controls' vestibular cerebellar GM density negatively correlated with perception and VOR. Diffusion-tensor imaging showed that cerebral cortex white matter (WM) microstructure correlated with vestibular perception but only in controls. In summary, dancers display vestibular perceptuo-reflex dissociation with the neuronatomical correlate localized to the vestibular cerebellum. Controls' robust vestibular perception correlated with a cortical WM network conspicuously absent in dancers. Since primary vestibular afferents synapse in the vestibular cerebellum, we speculate that a cerebellar gating of perceptual signals to cortical regions mediates the training-related attenuation of vestibular perception and perceptuo-reflex uncoupling.

Keywords: dancers, perceptuo-reflex uncoupling, training, vestibular-ocular reflex, vestibular perception

Introduction

Training-related expertize is associated with a level of performance that novices are unable to replicate and is associated with significant changes to brain structure (Zatorre et al. 2012). Most human studies of training-related brain plasticity have assessed the neuroanatomical correlates of expertize in motor or cognitive domains (Zatorre et al. 2012). In contrast, studies investigating the effect of sensory experience on human brain structure have been largely focused on cross-modal plasticity in individuals with early onset sensory deprivation (Noppeney 2007). Common to these studies is the presence of changes (increases or decreases) in both gray matter (GM) and white matter (WM), which correlate with superior performance (Bengtsson et al. 2005; Noppeney et al. 2005; Johansen-Berg et al. 2007; Hanggi et al. 2010; Taubert et al. 2010; Hüfner et al. 2011; Roberts et al. 2013).

The use of the vestibular system to probe brain plasticity is potentially very informative since perceptual and reflex processing of vestibular information can be simultaneously assessed providing a unique opportunity to investigate the effects of training on high- and low-order sensory function. The effect of training on vestibular processing is exemplified by ballet dancers' ability to perform multiple pirouettes with minimal sensation of vertigo. Pirouetting elicits both the perception of rotatory self-motion (vertigo) and a reflexive vestibular-ocular reflex (VOR) response. Ballet dancers are able to suppress both the perceptual and reflexive (VOR) responses to rapid spinning (Osterhammel et al. 1968), which suggests that dancers' resistance to vertigo may be explained by a generalized attenuation of vestibular signaling. Alternatively, training may affect VOR and perception differentially, in which case training-related changes in perceptual and VOR responses would be dissociated. Based on the clinical observation of a differential change over time in perceptual and VOR responses during recovery from an acute neurological dysfunction (Seemungal et al. 2011), we hypothesized that ballet dancers would display a differential sensory processing of vestibular perception versus reflex function.

Although the neuroanatomical correlates of training-related plasticity mediating vestibular sensory processing have not been previously investigated, 2 previous studies assessed brain structure in dancers (Hanggi et al. 2010; Hüfner et al. 2011). Hanggi et al. (2010) compared whole-brain structure between 10 female dancers and a control group without any behavioral assessment. Hüfner et al. (2011) compared a priori selected brain regions (hippocampus and parieto-insular cortex) between 21 trained subjects, comprising ballet dancers, ice dancers, and slack liners, and an untrained control group. Hüfner et al. also assessed cognitive task performance allowing an analysis of cognitive performance relative to the brain structure. Thus, neither study correlated brain structure with behavioral measures of vestibular function. Hence, in our study, we recruited a homogenous group of 29 highly skilled dancers exposed to repeated vestibular stimulation as a result of years of training and a control group, matched for age, sex, handedness, and physical activity. We then specifically correlated laboratory measured vestibular parameters with GM density and WM brain microstructure in both groups. We employed a well-characterized method (Okada et al. 1999) for measuring simultaneous vestibular-reflex and perceptual responses. We used voxel-based morphometry (VBM) and diffusion-tensor imaging (DTI) to study GM and WM correlates of the vestibular psychophysical parameters, allowing us to test whether plasticity in reflex versus perceptual vestibular processing had distinct neural bases.

Materials and Methods

Subjects

Twenty-nine female dancers and 20 female age-matched controls with no dancing experience were recruited for this study after obtaining written informed consent approved by the local ethics committee, in accordance with the Declaration of Helsinki. Dancers were full-time students studying in London at the Royal Academy of Dance, London Studio Centre, or Central School of Ballet. All dancers started some form of dance training in childhood (at or before 6 years of age), and we specifically assessed ballet experience given its particular exposure to pirouetting. Ballet dancing experience was calculated (Hüfner et al. 2011) by multiplying the hours of ballet training per normal week by the number of years trained. Relative dancing experience was found by dividing the individual ballet dancing experience by the greatest dancing experience within the group. The controls were rowers recruited from local rowing clubs and were matched for age and level of physical activity. All participants were healthy right-handers with a handedness score over 40 as determined by the Edinburgh Handedness Inventory (Oldfield 1971). All subjects were naïve to the experimental set-up which, in summary, consisted of 2 sessions: A psychophysical data collection session assessing vestibular function in the laboratory and then a separate structural neuroimaging session.

Psychophysical Assessment

For each individual, we obtained simultaneous measures of the eye movement and perceptual responses to an angular velocity step (Okada et al. 1999; Fig. 1*A*). These behavioral data were then subsequently used to explore relationships with the brain structure. Whole-body rotations in the dark called "velocity steps" are frequently used in the clinical assessment of vestibular function (Fig. 1*A*). A velocity step consists of a rapid change in angular velocity. In our experiment, we used a standard clinical velocity step that involves rotating the subject from rest, that is, starting from a "constant" 0°/s and going to a "constant" 90°/s over 0.5 s. This velocity step evokes both reflexive eye movements (VOR) and a perception of self-rotation. The slow-phase eye velocity and perception of self-rotation responses are maximal at the onset of the velocity step and then subsequently decay in an exponential fashion, such that both responses are typically zero after 60 s. Since after 60 s of continued constant angular velocity (90°/s) rotation, there is no longer any vestibular activation (i.e. there is no VOR response and subjects feel that they are no longer turning), a second velocity step can be obtained by rapidly stopping the subject (from 90°/s to 0°/s over 0.5 s). This "stopping response" velocity step evokes perceptual and VOR responses that are identical in magnitude to those induced by the starting response, but are now oppositely directed. A minimum 60-s interval was used between the velocity steps. If nystagmus or turning of the wheel was observed after 60 s, then the recording was continued until the responses had dissipated before the next velocity step was applied.

Any exponential decay, including the VOR or perceptual responses following a velocity step, can be described by: $N(t) = N_0 e^{-kt}$, where t is the time, $N(t)$ the intensity of vertigo or VOR slow-phase velocity at time t, N_0 the initial (at $t = 0$) peak intensity of vertigo or VOR slow-phase velocity, e exponential function, and $1/k$ the exponential time constant (TC). The TC is roughly equivalent to the time taken for the slow-phase eye velocity (or intensity of vertigo perception) to decrease by 63.2% from an initial value. In healthy subjects, velocity step-induced slow-phase eye velocity and vertigo intensity both decline with a TC of around 15 s (Cohen et al. 1981; Okada et al. 1999). Thus, the duration of VOR and vertigo responses following a provocatory whole-body rotation is roughly 3 times that of the TC.

Psychophysical Apparatus and Protocol

Subjects were seated on a motorized friction free rotating chair (Contravez DC motor; torque 120 Nm) fitted with foot, arm, and head rests (Fig. 1*A*). White noise was delivered via a pair of speakers positioned behind the subject's head on the chair. Eight ocular motor and vestibular responses were obtained from 4 starting and 4 stopping velocity steps as described above.

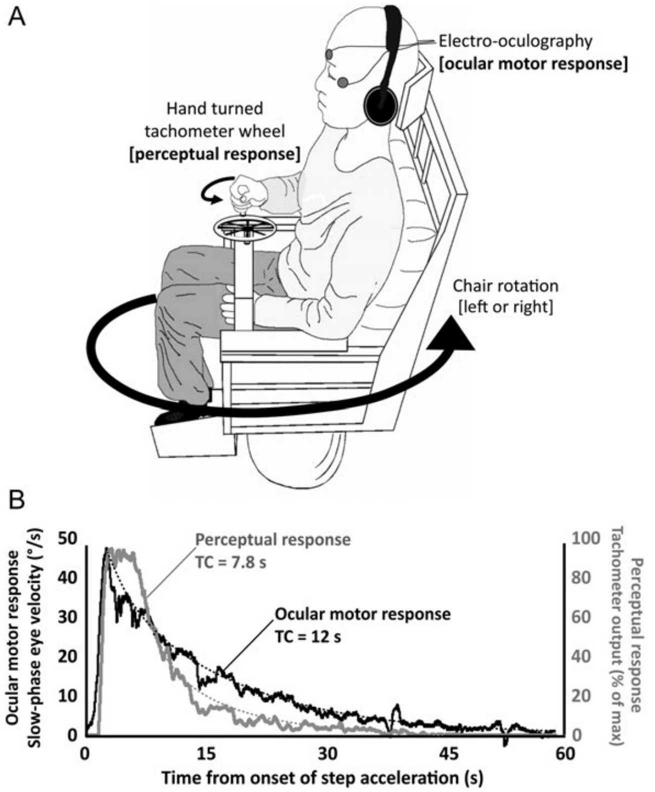

Figure 1. Experimental apparatus and raw records of vestibular-ocular motor and perceptual responses. (*A*) Subject sat on a motorized rotating chair in the dark. 90°/s velocity step rotations were administered (leftwards or rightwards). The subject's task was to rotate the tachometer wheel to match their sensation of rotation. Rotating the tachometer generates a voltage that indicates the subject's vestibular perception of self-motion. The voltage is digitally sampled and recorded at 250 Hz. VOR measures were obtained by measuring eye movements with standard EOG digitized at 250 Hz. (*B*) Example from a single subject of the raw signal from the tachometer wheel reflecting the perceptual response. The EOG signal has been calibrated, de-saccaded, and differentiated to provide a slow-phase eye velocity curve that reflects the ocular motor response. The dotted lines show the exponential decay curves from which perceptual and ocular motor TCs are calculated (the TC of any exponential decay can be estimated as the time taken, shown on the *x*-axis, for the response amplitude, and shown on the *y*-axis, to decrease by 63.2% of the initial value).

Vestibular-Ocular Reflex Measurement

Eye movements were recorded using horizontal binocular DC electro-oculography (EOG; Fig. 1*A*). At the start of the experiment, calibration of the eye position was performed by asking the participant to make 10°, 20°, 30° saccades to the right and left from the centre fixation target.

Vestibular Perception Measurement

The methodology used was identical to that described in Okada et al. (1999). Subjects indicated their perceived self-rotation by turning a wheel attached to the chair, which was connected to a tachogenerator. The tachogenerator's output voltage was proportional to the angular velocity of the wheel. The subjects were instructed to turn the tachometer wheel commensurate with their perceived self-rotation, which is maximal early on following a velocity step. The subjects were also instructed to turn the wheel more slowly as their sense of self-rotation died away and to eventually stop turning the wheel when they no longer perceived a sensation of self-rotation. This method enables the measurement of the relative change in the magnitude of vestibular perception during the time course of a velocity step response.

Data Analysis

EOG, chair motion, and tachometer wheel signals were recorded and stored at a sampling rate of 250 Hz. After calibration of eye position, EOG signals were differentiated and fast phases of VOR were removed to obtain slow-phase eye velocity curves (Fig. 1*B*). The wheel tachometer curves and the slow-phase eye velocity curves were averaged from the offset of the chair velocity keeping the left and right accelerations separate (Fig. 1*B*). Since no significant asymmetries were found (see results for Statistical Analysis), the responses from left and right accelerations were combined. Thus, the average wheel and the eye velocity curves consisted of 8 velocity step responses, which were then fitted with an exponential function with parameters estimated by Matlab® least square fitting algorithm (MatLab®, Mathworks, Optimization Toolbox) to determine the perceptual TC and the ocular motor TC, respectively.

MRI Data Acquisition and Analysis

Magnetic resonance (MR) imaging (MRI) data were acquired using a 1.5-T Siemens Magnetom Verio system and a 32-channel head coil. Whole-brain DTI data were acquired using spin-echo echo planar imaging in 30 spatial directions using b-values of 0 and 1000 s mm^{-2} [repetition time (TR) = 4.8 s; echo time (TE) = 140 ms; voxel size $1.8 \times 1.8 \times 4$ mm^3; number of averages = 3). Isotropic T_1-weighted anatomical images were acquired using an magnetization-prepared rapid acquisition gradient-echo (MPRAGE) sequence (TR = 1900 ms; TE = 2.48 ms; inversion time = 900 ms; flip angle = 9°; voxel size $1 \times 1 \times 1$ mm^3). All MRI data analyses were performed using FSL package, version 4.1.9 (www.fmrib.ox.ac.uk/fsl).

Gray Matter Preprocessing

T_1-weighted anatomical images were analyzed using FSL's implementation of VBM. Structural images were brain extracted and GM segmented using FAST before being nonlinearly registered to the standardized Montreal Neurological Institute (MNI) space to generate a study-specific template (Andersson et al. 2007). All native GM images were then registered to the study-specific template and modulated to correct for local geometric expansion/contraction. Finally, the modulated GM volumes were smoothed with an isotropic Gaussian kernel with a sigma of 2 mm (~4.7 mm full-width at half-maximum).

White Matter Preprocessing

Diffusion data were corrected for eddy-currents and head motion using affine registration to the average of nondiffusion-weighted volumes. DTI data were then skull stripped using the brain extraction tool (BET). A fractional anisotropy (FA) map was generated by fitting a diffusion-tensor model to the corrected diffusion data at each voxel using the FMRIB's diffusion toolbox. Voxel-wise statistical analysis of FA map across subjects was performed using tract-based spatial statistics (Smith et al. 2006). All subjects' FA was registered to the MNI_T_1_1 mm_brain using nonlinear registration and then projected onto a skeleton derived from a mean FA image.

Statistical Analysis

GM and WM analyses were performed using permutation-based nonparametric testing within the general linear model framework (Nichols and Holmes 2002). Results were considered significant for $P < 0.05$, corrected for multiple comparisons using threshold-free cluster enhancement (TFCE with 5000 permutations), an approach that avoids the choice of an arbitrary threshold for initial cluster formation (Smith and Nichols 2009).

Gray Matter Analysis. The image for each participant was entered in the design matrix along with group (dancers or controls) and brain size as covariates. A whole-brain voxel-wise comparison analysis was performed to identify differences in the GM density between the dancers and controls. The comparisons were (1) dancers' GM density greater than controls GM density (dancers > controls) and (2) controls' GM density greater than dancers' GM density (controls > dancers).

To explore the relationship between ocular motor and perceptual TCs, we performed a second analysis using ocular motor TCs, perceptual TCs, and brain size as covariates. This design enabled us to analyze the relationship between GM density and vestibular psychophysical measures. Psychophysical measures (ocularmotor and perceptual TCs) were modeled separately, so that covariate-by-group interactions could be examined. The relationships between GM density and psychophysical measures were tested using t-test contrasts to examine: (1) Unique correlations for each measure in each group; (2) correlations for each measure across the 2 groups; (3) average effect or interactions across the 2 measures in each group. Data were analyzed at a whole-brain level. Regions where GM density differences were detected between the groups in the comparison analysis were used as a mask to perform the subsequent voxel-wise correlation analysis.

White Matter Analysis. WM statistical analysis was performed using the same design matrices and procedure described above. The level of FA between the dancers and the control group was examined using the whole-brain voxel-wise comparison analysis (dancers > controls; controls > dancers). A whole-brain correlation analysis was then performed to test for specific WM-vestibular relationships using t-test contrasts as described in the GM analysis above.

The mean GM density and FA levels from the significant clusters obtained in the voxel-wise comparison and correlation analysis were used to perform post hoc linear regression analysis using the SPSS Statistics 20 software package to test for effects of dancing experience and, for illustrative purposes, to show correlations with the vestibular measures.

Results

Dancers had an average of 16 years of ballet training (standard deviation, SD = 4.2 years, range 3–24 years) and spent 3–20 h (mean = 8.8, SD = 3.7) of ballet training per week. Ballet experience (i.e. average hours of ballet per week multiplied by years trained; Hüfner et al. 2011) was 131.7 (SD = 47) with the maximum of 225. Controls were 21.2 years of age on average (SD = 4.6 years), matched to the age of the dancers (mean = 21.9 years, SD = 3.5 years), and exercised on average 7.2 h (SD = 3.4 h) every week.

Psychophysical Analysis

Ocular motor and perceptual responses were obtained from pre- and postchair rotations. There were no significant differences between leftward and rightward accelerations, and so they were combined ($P > 0.05$, $F = 1.32$, df = 1, factor: Direction of rotation, repeated-measures analysis of variance). Ocular motor TCs ranged from 9.52 to 15.8 s in dancers (mean = 11.7 s, SD = 1.78) and from 11.6 to 18.8 s in controls (mean = 14.9 s, SD = 1.87). Perceptual TCs ranged from 3.1 to 11 s in dancers (mean = 7.24 s, SD = 2.17) and from 5 to 14.5 s in controls (mean = 8.89, SD = 2.68). Dancers had significantly shorter ocular motor ($t = -5.83$, $P < 0.001$) and perceptual TC ($t = -2.36$, $P < 0.05$) than controls (Fig. 2*A*). Ocular motor and perceptual TCs were significantly correlated for controls (Fig. 2*B*; $r = 0.46$, $P < 0.05$) but not for dancers (Fig. 2*B*; $r = 0.11$, $P > 0.05$), demonstrating that, at the behavioral level, the normal association between reflex (VOR) and perception (Okada et al. 1999) seen in controls is lost in dancers. The gain in the VOR, calculated as eye velocity divided by chair velocity (90°/s), was not significantly different between the 2 groups ($P > 0.05$, t-test), with a mean gain of 0.51 (SD = 0.17) for dancers and 0.55 (SD = 0.13) for controls.

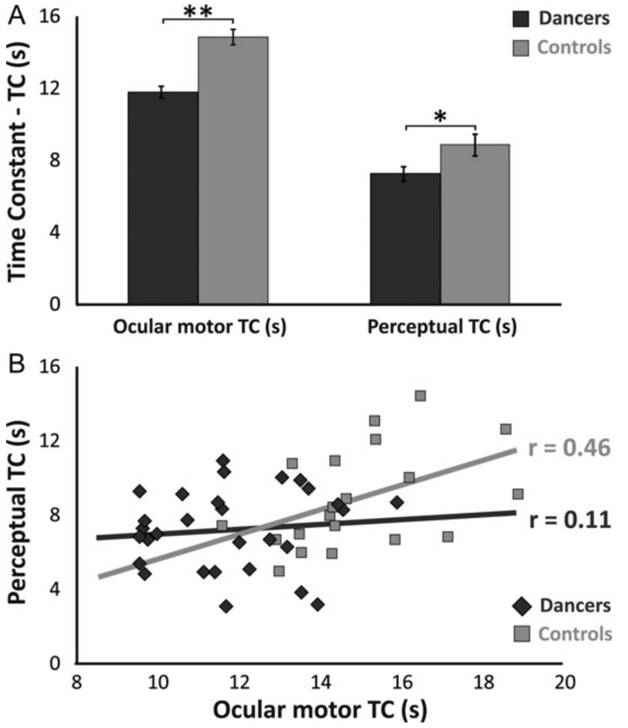

Figure 2. Results of psychophysical assessment. (*A*) Dancers showed reduced ocular motor and perceptual TCs when compared with the control group. Data marked ** is significant at $P < 0.01$; data marked * is significant at $P < 0.05$. (*B*) Controls, but not dancers, showed a significant correlation between ocular motor and perceptual TCs.

Imaging Results

A whole-brain voxel-wise comparison analysis comparing the GM and WM between the 2 groups was performed using a single design matrix. A second design matrix was employed to perform the voxel-wise correlation analysis with the vestibular psychophysical measures. We reported all significant findings at a significance level of $P < 0.05$ corrected for multiple comparisons. For clarity, the significant findings have been split under subheadings, which discuss each finding separately.

Gray Matter Analysis

Ballet Dancing Is Associated with Reduced Gray Matter Density in the Vestibular Cerebellum

A whole-brain voxel-wise comparison analysis comparing GM in the dancers with controls showed significant reductions in the posterior cerebellum bilaterally (Fig. 3*A*) in lobules VIII and IX [right cerebellum region: $t_{\max} = 4.21$, $P < 0.05$, size = 400 voxels ($x = 20$, $y = -58$, $z = -58$ mm); left cerebellum region: $t_{\max} = 4.67$, $P < 0.05$, size = 103 voxels ($x = -18$, $y = -62$, $z = -62$ mm); corrected for multiple comparisons; Fig. 3*A*]. Lobules VIII and IX form part of the vestibular cerebellum, a region that is important for vestibular processing in humans (Barmack 2003; Kheradmand and Zee 2011). Post hoc correlation analysis revealed that the mean GM of the significant cerebellum cluster negatively correlated with dancing experience (Fig. 3*B*; $r = -0.39$, $P < 0.05$). Therefore, dancers with greater experience tended to have smaller vestibular cerebellar GM density.

A single area in the right superior orbito-frontal cortex showed an increased GM in the dancers [dancers > controls; $t_{\max} = 3.32$, $P < 0.05$, size = 28 voxels ($x = 26$, $y = 66$, $z = 2$ mm)].

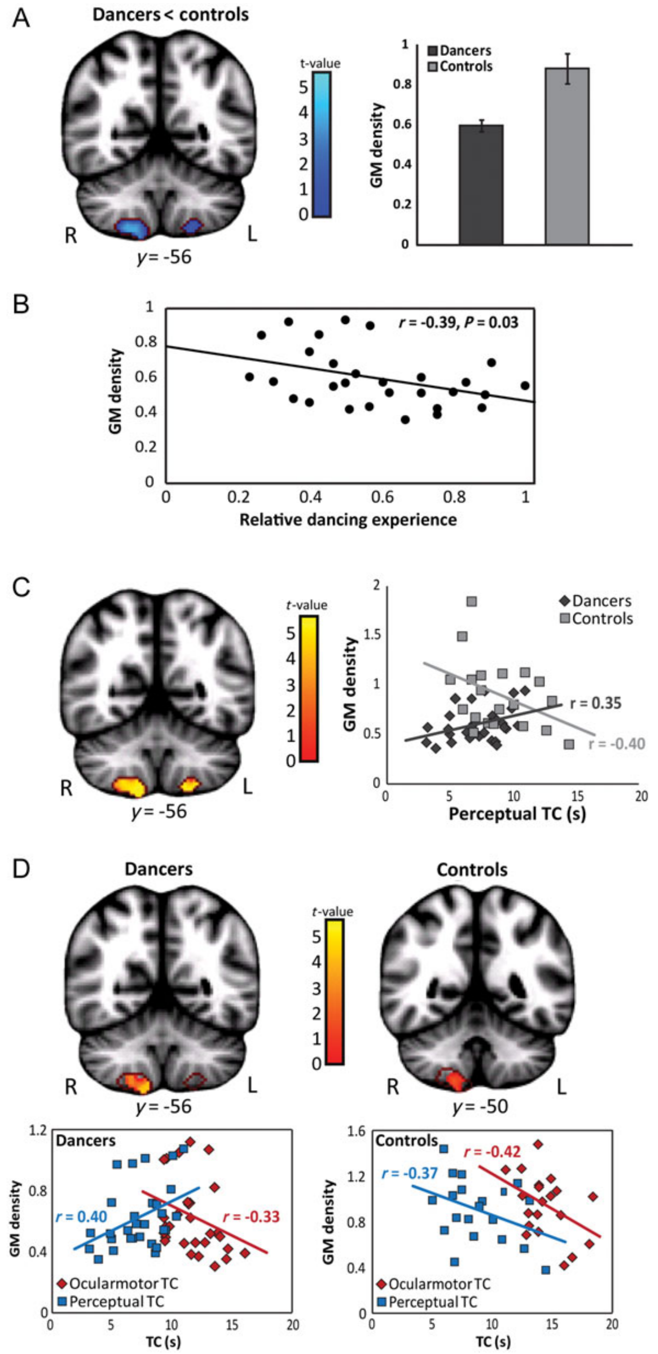

Figure 3. Results of GM analysis. (*A*) Whole-brain GM comparison showed a reduction in GM density in the posterior cerebellum in dancers compared with controls (dancers < controls). This region was then used as a mask (brown outline shows the edges of the mask) in subsequent GM analyses (*C* and *D*). The inset graph on the right shows the mean GM density of the significant posterior cerebellum region in the 2 groups. (*B*) The mean GM density of the significant cerebellum regions from dancers < controls analysis (*A*) negatively correlates with the relative dancing experience (1 = maximum dancing experience). (*C*) Intergroup interaction revealed a cluster, where GM density shows opposing correlations for perceptual TCs in dancers and controls. (*D*) In dancers, a significant cluster (left panel) was found in which GM density correlates negatively with ocular motor TC and positively with perceptual TC. In controls, significant cluster (right panel) was found where GM density negatively correlates with both ocular motor and perceptual TCs. (*C* and *D*) The inset graphs, with corresponding *r* values, illustrate the correlations by plotting the mean GM value of the significant cluster for each subject with the corresponding psychophysical measures. (*A*, *C*, and *D*). The significant clusters are shown at $P < 0.05$ (corrected) superimposed on a structural T_1 image (gray) in the coronal view with a Talairach coordinate (mm). Bar indicates *t* values. R: right; L: left.

We did not have any a priori hypothesis for such a cortical cluster; however, recent data (Taubert et al. 2010) support a role for this region in balance training (see Discussion section).

Dancers Show an Abnormal Relationship Between Gray Matter Density and Vestibular Perceptual Processing in the Vestibular Cerebellum

We then investigated the relationship between GM structure and vestibular processing in the posterior cerebellar region showing a group difference in the structure. In this region (posterior cerebellum; Fig. 3*C*), we found a significant interaction between groups and the relationship between GM structure and perceptual TC. Specifically, in this posterior cerebellar region, the correlation between perceptual TCs and GM was positive ($r = 0.35$) for dancers but negative ($r = -0.40$) for controls [Fig. 3*C*; right cerebellum cluster, $t_{\max} = 3.71$, $P < 0.05$, size = 371 voxels ($x = 14$, $y = -46$, $z = -60$ mm); left cerebellum cluster, $t_{\max} = 3.87$, $P < 0.05$, size = 96 voxels ($x = -18$, $y = -62$, $z = -60$ mm); corrected for multiple comparisons]. Therefore, dancers and controls share a region in the posterior cerebellum, where GM density correlates with perceptual TCs but critically in an incongruent manner between groups.

Dancers and Controls Show a Similar Relationship Between Gray Matter and Ocular Motor Processing in the Vestibular Cerebellum

A similar analysis was also performed to investigate the relationship between GM and the ocular motor TC. In contrast to perceptual processing, ocular motor TCs were negatively correlated in both dancers ($r = -0.37$) and controls ($r = -0.36$) with GM density in the posterior cerebellum [$t_{\max} = 3.82$, $P < 0.05$, size = 181 voxels ($x = 14$, $y = -44$, $z = -56$ mm); corrected for multiple comparisons], with no areas showing a group interaction for this relationship. Therefore, dancers and controls share a region in the posterior cerebellum where GM density correlates with ocular motor TCs in a congruent manner between groups.

Gray Matter Correlates of Vestibular Perceptual Adaptation

Within the 2 groups, we then investigated the relationship between GM and ocular motor and perceptual TCs. For dancers, GM density in part of the vestibular cerebellum was negatively correlated ($r = -0.33$) with ocular motor TCs, but positively correlated ($r = 0.40$) with perceptual TCs [Fig. 3*D*, left panel; $t_{\max} = 3.53$, $P < 0.05$, size = 268 voxels ($x = 12$, $y = -46$, $z = -62$ mm); corrected for multiple comparisons]. In contrast, for controls, GM density was negatively correlated for both ocular motor ($r = -0.42$) and perceptual ($r = -0.37$) TCs in a partially overlapping part of the vestibular cerebellum [Fig. 3*D*, right panel; $t_{\max} = 3.24$, $P < 0.05$, size = 94 voxels ($x = 14$, $y = -44$, $z = -56$ mm); corrected for multiple comparisons]. Therefore, in controls, both a shorter VOR and perceptual TC are associated with greater vestibular cerebellar GM density. In dancers, shorter VOR TCs are associated with greater vestibular cerebellar GM density, but shorter perceptual TCs are associated with smaller vestibular cerebellar GM density. Given that shorter TCs are the hallmark of adaptation as seen in dancers, these data imply that in the adapted state (dancers) but not in the normal state (controls), the relationship between GM density and function is dissociated between reflex and perception.

White Matter Analysis

Dancers and Controls Show a Similar Relationship Between White Matter and Perceptual Responses in the Temporo-Parietal Region

A whole-brain WM analysis showed a WM cluster (Fig. 4*A*), where the relationship between FA and perceptual TC was the same for both groups (i.e. here, FA positively correlated with perceptual TCs for both groups with $r = 0.50$ for dancers and $r = 0.81$ for controls). The WM cluster was largely within the superior longitudinal fasciculus, with the cluster maximum in the temporo-parietal region [$t_{\max} = 4.67$, $P < 0.05$, size = 10 659 voxels ($x = -35$, $y = -27$, $z = 44$ mm); corrected for multiple comparisons]. The temporo-parietal cortex is an area previously proposed to have a prominent role in processing vestibular sensations (zu Eulenburg et al. 2012). Note that no such relationship was found between the groups for ocular motor TCs and cortical FA, in any cortical WM region.

Dancers and Controls Show a Different Relationship Between White Matter and Perceptual Responses in the Frontal Cortical Region

Figure 4*B* shows the WM region (primarily the inferior fronto-occipital fasciculus and anterior thalamic radiation) within which FA levels showed an opposite relationship with perceptual TCs in dancers versus controls [$t_{\max} = 4.58$, $P < 0.01$, size = 205 voxels ($x = 26$, $y = -28$, $z = 28$ mm), corrected for multiple comparisons; $r = -0.42$ for dancers and $r = 0.79$ for controls].

Therefore, vestibular perceptual measures correlated in a similar manner in both groups with WM microstructure in temporo-parietal regions, but correlated differently in the regions extending into the frontal cortex.

Lack of White Matter Neuroanatomical Correlate for Perceptual Responses in Dancers

In the dancers' group, we found no WM clusters displaying significant correlations with perceptual TCs. In contrast, in the controls, we found a widespread bilateral cortical WM network where the FA level showed a highly significant positive correlation ($r = 0.79$) with perceptual TCs [Fig. 4*C*; $t_{\max} = 5.52$, $P < 0.05$, size = 40 145 voxels ($x = 26$, $y = -28$, $z = 28$ mm); corrected for multiple comparisons], with the cluster maximum in the right temporo-parietal WM. At higher significance level, $P < 0.001$ corrected for multiple comparisons, the significant voxels were found in the right hemisphere only [$t_{\max} = 5.52$, $P < 0.001$, size = 1096 voxels ($x = 26$, $y = -28$, $z = 28$ mm)], suggesting a right hemisphere dominance for the neuroanatomical correlates of perceptual response.

In summary, the DTI analyses showed that perceptual TCs correlated with an extensive cortical WM microstructure network in the controls, a finding notably absent in dancers. In addition, a common temporo-parietal region was identified where WM microstructure (FA) correlated with perceptual TC in the same way in both groups.

Discussion

We demonstrate that the normal association between reflex and perceptual vestibular function is uncoupled in individuals adapted to long-term repetitive vestibular stimulation and the neuroanatomical correlate of this uncoupling is localized to the vestibular cerebellum. Moreover, we show that dancers have reduced GM density in the vestibular cerebellum (specifically

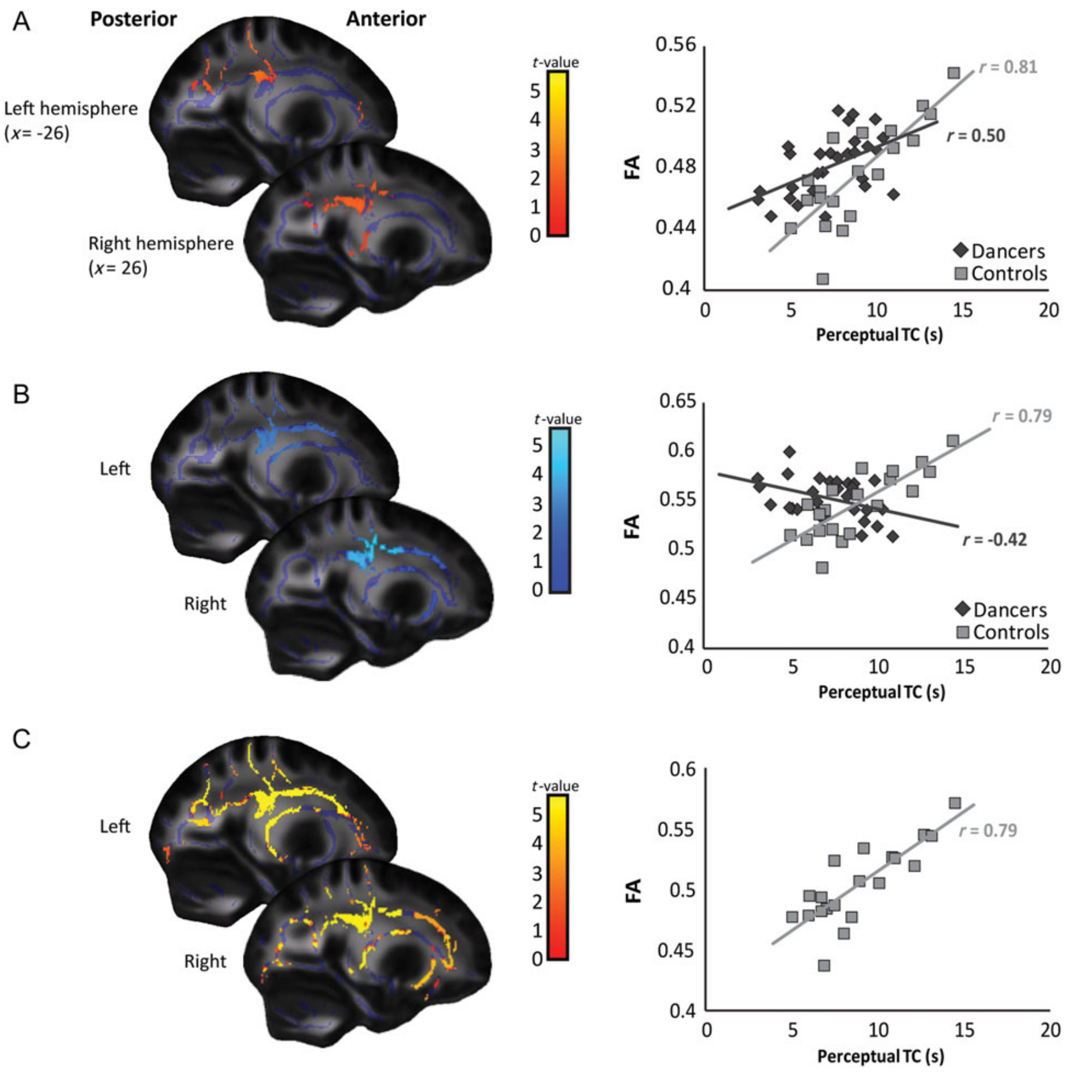

Figure 4. Results of the WM analysis. (*A*) Whole-brain correlation analysis revealed significant WM regions, where FA positively correlates with perceptual TCs in both dancers and controls. (*B*) Significant WM regions in which FA positively correlates with perceptual TCs in controls and negatively correlates with TCs in dancers. (*C*) A positive correlation between WM FA levels and individual perceptual TC values in a widespread cortical WM network (orange) in the control group only. (*A*–*C*) Color bars indicates *t* values. The inset graphs, with corresponding *r* values, demonstrate the correlations of the mean FA value of the significant cluster for each subject with perceptual TCs. All significant clusters are shown $P < 0.05$ (corrected) superimposed on a structural T_1-image (gray) and the skeletonized FA image (blue). Sagittal views of the right and left hemispheres are shown for each analysis. The right hemisphere view is of a plane defined by the "$x = 26$" Talairach coordinate (mm) and the left hemisphere by the "$x = -26$" Talairach coordinate (mm). Anterior and posterior are as indicated.

in lobules VIII and IX), which is correlated with dancing experience. These results suggest that training-related cerebellar changes can differentially affect the processing of vestibular perception versus reflex function. We also show that a measure of vestibular perception that correlated with WM microstructure in a cerebral cortical network in controls was not observed in dancers, an observation that may be behaviorally relevant since dancers show attenuated vertigo responses compared with controls.

Behavioral Measures of Vestibular Perceptuo-Reflex Coupling

Normally, perceptual responses are tightly coupled with low-order reflex responses allowing a prediction of one from the other. Our finding of a correlation between VOR and perceptual TCs in the control group replicates previous reports of such a correlation in healthy individuals (Okada et al. 1999) and cerebellar patients (Bertolini et al. 2012). In contrast, we found that dancers' perceptual and reflex TCs were uncorrelated (Fig. 2*B*), demonstrating that purposeful adaptation to chronic vestibular stimulation leads to both an uncoupling of perceptuo-reflex congruency and attenuation of vertigo sensation. An uncoupling of vestibular perception and reflex is also seen in patients recovering from transient ocular motility deficits (Seemungal et al. 2011) or with experimental habituation in healthy volunteers (Guedry et al. 1992; Merfeld et al. 2005; Clement et al. 2008). One implication is that an uncoupling of vestibular perception and reflex is an advantageous behavioral response to vestibular training (including vestibular physiotherapy) or in the recovery from a peripheral or central vestibular dysfunction. For example, in patients with a fixed right-left asymmetry in peripheral vestibular function, head movements that would not ordinarily evoke a postmovement vestibular response may result in a vestibular activation with nystagmus and a sensation of vertigo. Effective perceptuo-reflex uncoupling could, however, suppress vertigo in such a case. Thus, if perceptuo-reflex uncoupling could be specifically enhanced by vestibular physiotherapy, then this could result in symptom suppression despite moderate degrees of peripheral vestibular dysfunction.

Gray Matter Correlates of Perceptuo-Reflex Coupling

In addition to a behavioural uncoupling (Fig. 2*B*), our data show that the vestibular-ocular and perceptual functions are also uncoupled at the neuroanatomical level in dancers (Fig. 3*D*). The vestibular cerebellum is known to be critical for modulating both the VOR TC and the vestibular perceptual TC (Waespe et al. 1985; Kheradmand and Zee 2011). Previous reports demonstrating a correlation between vestibular-ocular and perceptual TCs (Okada et al. 1999; Bronstein et al. 2008; Bertolini et al. 2012) suggest the concept of a single vestibular cerebellar mechanism mediating vestibular-ocular and perceptual processing. In contrast, pharmacological manipulation of cerebellar function (Shaikh et al. 2013) differentially affected VOR and perceptual TCs, implying at least some degree of functional distinction between cerebellar circuits processing VOR versus vestibular perception. Our current data confirm that the cerebellum processes both vestibular-ocular and perceptual signals but with a degree of functional and neuroanatomical separation. This would enable vestibular adaptation to differentially affect ocular or perceptual function according to ecological need as discussed in the previous section.

In dancers, a postpirouette reduction of vertigo is critical for maintaining their balance and spatial orientation. Hence, during the early stage of training, the active effort to suppress dizziness potentially results in a top-down modulation of subcortical neuronal networks, specifically those that are implicated in relaying signals to perceptual regions. In the long term, this may result in the altered functional and anatomical relationship between vestibular cerebellar GM and perception, as seen in our findings. The finding of vestibular head motion signals in the vestibular cerebellum would be a prerequisite for the notion that the vestibular cerebellum is involved in vestibular perceptual modulation. Indeed in support of this, Yakusheva et al. (2007) demonstrated the encoding of signals of head motion (in an inertial rather than egocentric reference frame) in primate cerebellar Purkinje cells in the posterior vermis. Additionally, vestibular cerebellar Purkinje cells encode head attitude, that is, orientation in space (Yakusheva et al. 2007), the maintenance of which is critical for a dancer coming out of a pirouette. These data combined with our current findings emphasize the importance of the vestibular cerebellum in the differential processing of vestibular-ocular versus perceptual signals. Note that the attenuation of vestibular signals of self-motion should not impair dancers' dynamic balance, since their rapid movements are highly choreographed and primarily use feed-forward ballistic motor signals. In addition, static balance depends critically on proprioception as evidenced by the gross impairment of balance control in proprioceptive loss patients (Sheikh and Amato 2010), which contrasts to the common clinical observation that chronic vestibular loss patients can regain near-normal balance using other sensory inputs.

Our finding of a training-related reduction of GM density in dancers' vestibular cerebellum (implying beneficial brain plasticity) contrasts with most previous reports showing increases in brain GM (often cerebral cortex) in relation to skill acquisition (Maguire et al. 2000; Draganski et al. 2004; Boyke et al. 2008; Ilg et al. 2008; Scholz et al. 2009; Taubert et al. 2010). Relatively, few studies have reported reductions in GM following training or in expert groups (Hanggi et al. 2010; Taubert et al. 2010; Hüfner et al. 2011), but interestingly, these included 2 studies with ballet dancers reporting GM density reductions albeit in cortical areas (Hanggi et al. 2010; Hüfner et al. 2011). Our study differs from these 2 previous ballet dancer studies since they used a priori hypothesized cortical areas of interest (Hanggi et al. 2010; Hüfner et al. 2011), whereas we used a whole-brain analysis. Additionally, neither study measured vestibular behavioral parameters, and one study (Hüfner et al. 2011) recruited a trained group that included nondancers.

That both cerebellar atrophy patients and dancers show reduced cerebellar GM density does not, however, equate to equivalent behavioral functioning between the groups. Cerebellar patients may display either increased or decreased TC durations (Hain et al. 1988; Heide et al. 1988; Jeong et al. 2007; Bertolini et al. 2012), whereas as a group dancers show consistent reductions in TC duration. Secondly, cerebellar patients' perceptual and reflex TCs are correlated (Bronstein et al. 2008; Bertolini et al. 2012). One explanation for dancers' GM loss could relate to the age and duration of training since dancers typically start training in childhood (Penhune 2011). In comparison, previous studies showing training-dependent GM enlargement involved learning a new skill over weeks to months (Draganski et al. 2004; Boyke et al. 2008; Scholz et al. 2009). Indeed, although training-related GM increases occur in early phases of learning, once learning is established, GM density reverts back to original levels with maintained performance (Driemeyer et al. 2008). Another explanation for lower cerebellar GM in dancers may relate to the degree of automaticity of the task. Since dancers would always want vertigo suppression, a hard-wired circuit with little flexibility could suffice, resulting in GM loss in tandem with training. In contrast to our cerebellar findings, conspicuous in our whole-brain GM analysis was a single cortical cluster showing increased GM density in dancers in the superior orbito-frontal cortex. This region was previously identified (Taubert et al. 2010) as correlating with motor performance in a whole-body balancing task. One faculty that should be expanded in dancers and requiring high levels of flexibility (in stark contrast to the vestibular TC) would be a repertoire of motor skills consequent upon years of dance training. Whether such a faculty could relate to this lone cortical GM expansion and whether the GM expansion relates to greater behavioral flexibility are speculative.

Cortical White Matter Neuroanatomical Correlate of Perceptual Measures in Controls

Our study is the first to our knowledge to assess vestibular processing using DTI analysis. Our main DTI result was that vestibular perceptual measures strongly correlated with a widespread cortical bilateral WM (FA) network in controls, implying that self-motion perception is mediated by a network of cortical regions (Fig. 4*C*). In contrast, an identical within group analysis for dancers did not show any correlation between cerebral cortex WM microstructure and vestibular perception. Dancers are notably resistant to vertigo, and this vertigo resistance could be related to a relatively poorly developed WM network mediating self-motion perception. Note that the lack of DTI correlation with dancers' perceptual TCs was unlikely to be simply related to a reduced range of their TCs available for the correlation since their TC range was similar to the controls. Finally, an important negative finding was that cortical DTI measures did not correlate with ocular TCs in any group confirming the importance of subcortical structures for automatic ocular processing.

To identify a common core region mediating vestibular perception, we assessed brain regions showing a congruent relationship between groups for perception and WM microstructure (Fig. 4*B*). Our DTI analysis showed, consistent with the previous data, that the WM in the temporo-parietal region appears to represent a core vestibular perceptual region (Brandt and Dieterich 1999; Kahane et al. 2003; zu Eulenburg et al. 2012). Moreover, in controls, this network appeared predominantly in the right hemisphere (see Results section "WM analyses"), supporting the lateralization of vestibular processing (Dieterich et al. 2003).

What might be the link between the cerebellar GM and cortical WM behavioral correlates in dancers? Assuming that dancers' reduced self-motion perception is, indeed, reflected in a less well-developed cortical network for processing vestibular perceptual signals, then one explanation is of a cerebellar gating of vestibular signals of self-motion perception to the cortex. Recent evidence suggests that normally, the cerebellum selectively suppresses vestibular signals generated by active self-motion and not those due to passive movements (Brooks and Cullen 2013). In dancers, such cerebellar gating could extend to involve the suppression of passively generated vestibular signals and as a result, lead to a less well-developed WM network mediating vestibular perception of self-motion. This hypothesis could be tested by prospectively imaging subjects (with a suitable control group) before and after a vestibular habituation protocol with vestibular behavioral testing (Clement et al. 2008).

Limitations

Given the cross-sectional nature of our study, we cannot exclude the possibility that our findings relate to inherent differences in individuals who are predisposed to become ballet dancers rather than the training they undergo. That GM changes were localized to the vestibular cerebellum and that the degree of GM changes were correlated with dancing experience suggest that these changes were training-related rather than due to interindividual predisposition. Another potential confound is that dancers' training involves other non-vestibular types of adaptation. Our approach minimizes the potential misallocation of nonvestibular function to structure by specifically correlating vestibular-related measures (of perception and reflex) to structure.

Relevance and Implications

Understanding the brain mechanisms underlying vestibular adaptation and its impact on reflex and perceptual vestibular mechanisms is of fundamental importance to the approach, investigation and treatment of patients with chronic vestibular disorders. For example, our finding that vestibular-reflex and perception can be dissociated in both behavioral measure and neuroanatomical correlate is consistent with the observation that many patients with chronic vestibular symptoms show few abnormalities on standard vestibular testing (that interrogate vestibular-reflex and not perceptual function). The treatment of patients with chronic dizziness includes vestibular rehabilitation, a form of vestibular training. Since reflex and perception may respond differentially to training, treatment monitoring should include vestibular perceptual measures and not only traditional measures of VOR function.

Summary

In summary, we observed 2 main effects of long-term training involving vestibular adaptation; first, the congruent correlation between reflex and perception with vestibular cerebellar GM density is dissociated in dancers. Secondly, dancers display an attenuated WM network correlate of vestibular perception. We speculate that dancers' attenuated WM cortical network associated with vestibular perception reflects dancers' vertigo resistance. In addition, we suggest that vestibular cerebellar gating of ascending vestibular signals may result in this relatively attenuated WM cortical network mediating vestibular perception. If true, then cerebellar gating may, in effect, allow dancers to perform pirouettes at ease with little dizziness.

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