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What is straight ahead to a patient with torticollis?

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Summary

Vestibular and neck proprioceptive signals are known to be used in judging the locations of objects in space and relative to the body. Given that these signals are asymmetric in patients with spasmodic torticollis, one would expect such patients to have abnormal spatial perception. We tested this idea by measuring patients' perception of visual straight ahead (VSA) under various conditions: with the body in its primary position, i.e. with the head and trunk as closely aligned as possible, and after well defined passive rotations of the head and/or trunk. In the primary body position, patients' VSA direction showed considerable variations which were similar, however, to those of normal subjects; it was independent of torticollis direction, of the head torque it produced, and of the weak spontaneous nystagmus recorded in seven of the 10 patients. After whole-body rotations, i.e. where head and trunk underwent the same motion, the VSA was shifted in both patients and normal subjects, and in both groups the shift was symmetrical after rotations to the right or left. After motions where the trunk rotated under the stationary head (neck proprioceptive stimulation) or the head on the stationary trunk (combined vestibular and neck stimulus), the VSAs of normal subjects coincided rather well with their head midsagittal planes, whereas the VSAs of patients were shifted considerably towards the trunk, again in a symmetrical way. We suggest two mechanisms to explain the findings in patients: (i) a central compensation which restores symmetry of the afferent inflow in the patients (unlike the motor efference); (ii) shifting of the reference for the VSA from the head towards the trunk, because the trunk is a more reliable egocentric reference than the head in the patients. Our findings do not support the assumption that asymmetries in afferent inflow are responsible for the asymmetry of motor output in spasmodic torticollis.

Keywords: idiopathic spasmodic torticollis; visual straight ahead; spatial orientation; vestibulo-ocular reflex; proprioceptive neck stimulation

Abbreviations: ANOVA = analysis of variance; L_G = leftward (VOR) gain; NECK = (proprioceptive) neck stimulation; R_G = rightward (VOR) gain; VEST = vestibular stimulation; VEST+NECK = combined vestibular and neck stimulation; VOR = vestibulo-ocular reflex; VSA = (subjective) visual straight ahead

Introduction

Idiopathic spasmodic torticollis is the most common form of focal dystonia, but the pathophysiology of the abnormal head posture is still obscure. The extrapyramidal system appears to be involved, although the evidence is far from conclusive (Hedreen *et al.*, 1988). Sensory systems have been recently implicated in spasmodic torticollis and other dystonic syndromes (Hallett, 1995). Generally, sensory cortical inflow appears to be altered in dystonic patients, as judged from sensory evoked cortical potentials (Mazzini *et al.*, 1994) and changes in cerebral blood flow (Tempel and Perlmutter, 1990). More specifically, an imbalance of vestibular tone has been found in spasmodic torticollis patients, many of them showing spontaneous nystagmus and a directional bias of the vestibulo-ocular reflex (VOR) opposite to the direction of the torticollis (Bronstein and Rudge, 1986). Also, a special role has been attributed to the input from muscle spindles (Kaji *et al.*, 1995), in part because vibrating the neck muscles of spasmodic torticollis patients has been claimed to ameliorate their pathological head deviation (Leis *et al.*, 1992). Since spatial perception depends strongly on vestibular and neck proprioceptive afferents, these reports raise the question whether spasmodic torticollis patients perceive their spatial environment asymmetrically. In particular, we question the role of the head as a reference system in spasmodic torticollis patients, since for them it represents a rather unstable and poorly controlled platform.

Proprioception is often studied using muscle vibration as a stimulus. This stimulus excites primary muscle spindle afferents (Burke *et al.*, 1976; Roll and Vedel, 1982), whose activity is interpreted by the subject as indicating muscle lengthening and therefore a change in limb or body position. Accordingly, muscle vibration in normal subjects may lead to 'compensatory' adjustments of limb and body position (Goodwin *et al.*, 1972; Lackner, 1988). Vibration of neck muscles or their tendons may lead to illusory and/or actual movements of the head or whole body (Roll *et al.*, 1991; Taylor and McCloskey, 1991), and to an illusory displacement of a visual object being viewed by the subject (Biguer *et al.*, 1988; Roll *et al.*, 1991; Taylor and McCloskey, 1991). Studies using natural neck proprioceptive stimulation (head rotation relative to the trunk) have confirmed, in humans, that neck afferents are important in perceiving not only head posture (Mergner *et al.*, 1991) but also the motion and localization of visual objects (Mergner *et al.*, 1992; Maurer *et al.*, 1997). The same applies to visual target localization in monkeys (Andersen *et al.*, 1993; Brotchie *et al.*, 1995). Furthermore, an asymmetry in vestibular inflow in patients suffering from vestibular neuritis has been shown to distort egocentric localization (i.e. localization with reference to one's own body) of visual objects (Hörnsten, 1979). The body reference system is affected not only by asymmetries in sensory inflow, but also by cerebral lesions, e.g. in the right parietal cortex (Heilman *et al.*, 1983; Karnath, 1994).

Normal subjects use the term 'straight ahead' which coincides approximately with the direction of the body midsagittal plane. We asked what direction is thought of as 'straight ahead' by the spasmodic torticollis patients whose heads are chronically rotated. Given that the abnormal head posture in spasmodic torticollis patients is associated with asymmetries of neck proprioceptive input, of vestibular input, and/or of the central representation of these afferents, one might expect spasmodic torticollis patients to misjudge the positions of their own bodies. This in turn could lead to further problems with spatial perception and behaviour. We therefore assessed the perceived straight ahead direction in spasmodic torticollis patients in the absence of visual and auditory space cues, using a recently developed psychophysical procedure in which subjects set, with the help of a remote control, a light spot in the straight ahead direction with respect to their own body (Maurer *et al.*, 1997). The procedure was performed in the primary body position as well as after head and trunk positions had been varied in space, and relative to each other, by applying transient rotational vestibular, neck, and combined vestibular and neck stimuli in the horizontal plane. These stimuli were applied because we wanted to learn to what extent the responses of spasmodic torticollis patients are asymmetric; and what they use as an egocentric reference frame, i.e. whether they refer to their heads or trunks when solving the subjective 'visual straight ahead' (VSA) task. To complement these psychophysical data, we also measured the subjects' head torque during the rotational stimuli, and we assessed the symmetry of their vestibular tone, by measuring their spontaneous nystagmus in the dark and by comparing their VOR gains to the right and left.

Methods

Patients and control subjects

Ten spasmodic torticollis patients and 12 normal subjects gave their informed consent to the study, which was approved by the ethics committee of the Freiburg University Clinics. The two groups were matched with respect to age (43.0 ± 13.9 and 38.2 ± 12.9 years, respectively; means $\pm$ SD). Magnitude of neck dystonia was assessed in the patients when they were sitting at rest, by means of a large protractor using the severity scale of Tsui *et al*. (1986). In particular, head turn in the horizontal (transverse) plane of the body, tilt in the frontal plane and anteroposterior deviations in the sagittal plane were evaluated separately by referencing the chin–nasion line to the anterior median line of the thorax and by measuring the angle of the Reid's base line relative to the horizontal plane. For each of these planes the head deviation was quantified as absent (0), mild (grade 1; $<15°$), moderate (grade 2; 15–30°) or extreme (grade 3; $>30°$). Patients with prominent head jerks were excluded. Only one patient had a mild, continuous head tremor; in this case, score (2 in the tremor part of the scale) was added to the sum of the head deviation scores (Table 1).

All patients but one belonged to a group which was treated for spasmodic torticollis by regular botulinum toxin injections in the neck muscles. In order to minimize possible effects of botulinum toxin on muscle afferent inflow (see Discussion), the experiments were performed after an interval of at least 3 months following the last injection, and immediately prior to the new treatment. One patient had never been previously treated for spasmodic torticollis. This patient's results were essentially identical to those of the treated patients and therefore will not be considered separately. None of the patients or normal subjects took any drugs at the time of measurements.

Apparatus and stimuli

Subjects were seated on a Bárány chair (Toennies, Freiburg) in the centre of a cylindrical screen with a 1.6-m radius. During presentation of the stimuli, their heads were stabilized by means of a dental bite-board. The board was attached to a head holder which was mounted on the chair, but could be rotated independently from the latter in the horizontal plane. The shaft of the head holder contained a device for measuring head torque. The chair and head holder were rotated by independent position–controlled servomotors. A laser spot, subtending 0.2° of visual angle, could be projected onto the screen and moved horizontally by a mirror galvanometer, the axis of which was collinear with the rotation axes of the chair and head holder.

Table 1 *Clinical and experimental data from 10 patients with idiopathic spasmodic torticollis*

Patient	Age (years)	Disease duration (years)	Head turn at rest (°)	Severity score	Baseline straight ahead (°)	Spontaneous nystagmus (°/s)	Directional bias of VOR (%)
1	51	7	–25	3	–5.9	–2.5	–24.1
2	48	16	–15	3	5.3	–1.4	–6.6
3	51	4	35	4	–6.8	1.5	14.0
4	60	6	22	5	–2.8	0.8	4.0
5	61	4	–10	2	3.4	–1.9	–8.3
6	34	4	–35	5	–6.2	–2.2	–39.7
7	24	5	–8	3	0.6	–	0
8	36	6	–30	4	–9.4	–	0
9	21	3	–10	2	–4.1	1.2	13.0
10	44	6	–5	3	6.6	–	8.6

Positive values of the head turn signify deviation (in degrees) of the chin to the right, negative values deviation to the left. The spontaneous nystagmus was measured in darkness (positive values indicate slow phase velocity to the right), and for the VOR-directional bias, positive values indicate bias of rightward over leftward gain.

Whole-body rotation (in which the chair alone turned) was used to generate the vestibular (VEST) stimulation. Isolated neck (NECK) stimulation was obtained by rotating both the head holder and the chair about the same angle, but counter to each other, so that the head remained stationary in space. Rotating only the head holder, resulting in head rotation on the stationary trunk, was used to produce combined vestibular and neck (VEST+NECK) stimulation. The rotation trajectories showed a smoothed trapezoidal form, with the velocity profile being roughly bell-shaped (see Fig. 3 below). Angular displacement was kept constant (14°, towards either the left or the right side with respect to the primary position), while stimulus duration was varied (10, 5 and 1.25 s), measured peak angular velocity amounted to 2.3, 4.6 and 18.4°/s, and the respective dominant frequencies were 0.1, 0.2 and 0.8 Hz. These frequencies were adopted from the study of Maurer *et al.* (1997), who used them to distinguish between vestibular effects (showing a gain attenuation at low frequencies) and proprioceptive or visual effects (gain remaining constant across the frequencies).

The mirror galvanometer received two inputs. One input was generated by a computer and it stepped the laser spot 10° to either side (probe stimulus) and the other stemmed from a joystick which was handled by the subject during the psychophysical procedure (see below).

Auditory spatial cues were reduced with ear plugs. How well the subjects performed their experimental tasks was checked continuously by means of an infrared video camera.

Instructions and experimental procedure

Subjects were instructed to '. . . point the laser spot in the straight ahead direction. When the spot steps to one side or the other, bring it back to straight ahead as fast as possible'. The subjects were instructed to operate the lever of the joystick with the right hand, and were given the opportunity to practice the task in the light.

Prior to the testing, care was taken so that the head and trunk of normal subjects were aligned with each other (i.e. their heads were facing approximately the direction of their bodies' midsagittal planes). With the patients we tried to minimize, as far as possible, the abnormal head deviation and to achieve orthotropia without producing discomfort. The degree of the remaining deviation was recorded. The subjects were instructed to relax their neck muscles as much as possible and not to resist or to help actively any imposed head rotation.

Trials consisted of three parts (see Fig. 1). First, baseline recordings were made. We turned out the room lights and measured the subjective VSA with the head and trunk in the starting (primary) position. For this measurement, the laser spot stepped three times in each direction (inter-step interval 2.5 s; step direction changed after each second step). After each step, the subject brought the laser spot back to straight. Secondly, a test stimulus (VEST and/or NECK) was applied in complete darkness. Thirdly, 2 s after the end of the stimulus, the VSA was again measured, by the same six-step procedure, to see how it had been affected by the stimulus. Thereafter head and trunk were returned to their starting positions and the subject was given a short break, during which the room was illuminated, in order to prevent after-effects influencing the next trial.

The test runs consisted of 18 such trials (three stimulus durations×two directions×three different test stimuli) in random order and lasted, in total, 30–40 min. Rest periods of several minutes were allowed after three or four trials.

Data acquisition and analysis

Position readings of the two galvanometer inputs (joystick, step signal), of the galvanometer output (object position on the screen; in degrees), of chair and head holder potentiometers (in degrees), of the torque applied to the head holder (in newton metres), and of the on–off signal of the laser beam were sampled at 200 Hz and stored in a computer for off-line analysis. The last 20 data points that preceded each step displacement of the laser spot were marked with

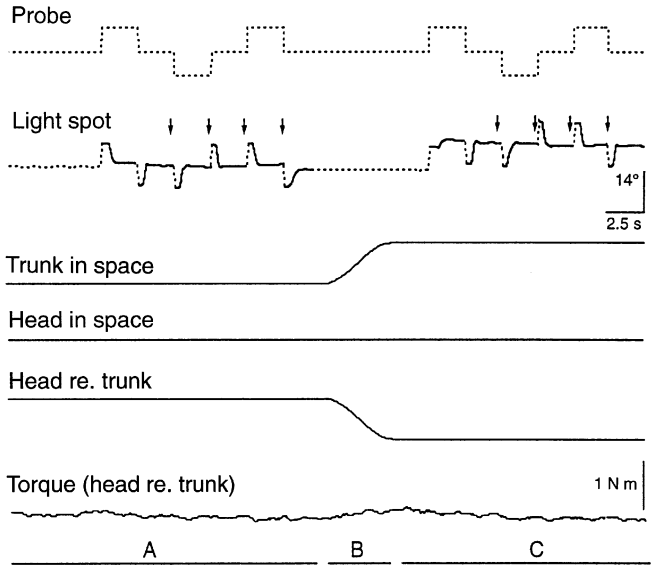

Fig. 1 Experimental paradigm used to evaluate the 'visual straight ahead', i.e. VSA (original example from a patient). Baseline measurements (head and trunk in primary position) are taken during interval 'A'. The patient views a light spot that is projected via a mirror galvanometer (probe) onto a cylindrical screen, and adjusts the spot to the straight ahead direction by means of a joy stick (signal not shown). The second trace shows the resulting position of the light spot (unbroken line = spot visible; broken line = spot extinguished). The patient repeats this sequence six times following computer-generated steps of the spot, 10° either to the right or left side (trace 'probe'). Arrows indicate times and spot positions when data are collected for analysis. The head and/or trunk are rotated, in complete darkness, during the interval 'B'; in this example the neck is stimulated (NECK stimulus) because the trunk is rotated while the head position remains fixed in space; i.e. the patient's trunk is rotated in space 14° to the right (up) and his head relative to the trunk at the same time and by the same amount to the left, such that his head remains stationary in space. Response measurements are taken during interval 'C'; each time the spot reappears, the patient again brings it back to his VSA direction. Note that this has shifted in the direction of the trunk compared with that recorded in A.

an interactive computer program (Fig. 1, arrows) and, if accepted as baseline or response values, were stored as displacement values in relation to the primary chair and head-holder positions. Equal numbers of rightward and leftward steps were analysed, because a step to a given side in itself slightly biases the VSA towards the same side (positive after-effect; Maurer *et al.*, 1997). The mean of the second to fifth responses was calculated (i.e. responses to four steps, two in each direction) for both the baseline and the responses after the VEST and/or NECK stimuli. The response to the test stimulus was compared with the baseline response (difference between the two mean values). The standard deviation across the second to fifth responses in the step sequences was taken to reflect judgement precision.

Eye movement measurements

Following the psychophysical experiments, eye movements were measured in normal subjects and patients to quantify any spontaneous nystagmus and VOR asymmetry. Recordings were performed in darkness by means of an infrared corneal reflection device (IRIS, Skalar; Delft, The Netherlands). Subjects were seated upright, with the head restrained as before (during the psychophysical judgements). The subjects were first asked to fixate on a stationary laser spot in front of them, presented with the body in primary position. For eye movement calibration, subjects fixated the spot while repeatedly being presented with the above 14° and 1.25-s VEST stimulus in the light. Thereafter, spontaneous eye movements were recorded for 2 min in the dark while subjects performed mental arithmetic. Finally, VOR to the left and to the right was elicited by applying the just mentioned VEST stimulus 300 ms after spot extinction, four times in each direction. The VOR gain (i.e. negative quotient of 'eye-in-head' to 'chair-in-space' displacements) was calculated separately for head evoked eye movement to the left (L_G) and right (R_G), and directional bias was calculated according to the formula: $(R_G - L_G) \times 100/(R_G + L_G)$. Note that the directional bias reflects both static and dynamic components, whereas spontaneous nystagmus reflects only the static component.

Passively maintained head turns in normal subjects

Another study was performed to ascertain the effect of sustained head turn on judgements of straight ahead. In six of the above normal subjects (age range 28–60 years) the psychophysical testing was repeated in an extra session with the head held in a turned position throughout the session (to the left side in three subjects and to the right side in the other three subjects). This artificial bias was introduced by turning the head holder in the dark, prior to testing (combined VEST+NECK stimulus of 7° for 20 s). The subsequent 18 trials proceeded as above, but about the new, shifted starting position. The subjects were not explicitly informed about the change in the paradigm.

Statistical analysis

Significance of findings was tested with analysis of variance (ANOVA) unless stated otherwise. The analysis was performed twice, with and without normalizing the patients' data with respect to the horizontal direction of their torticollis (i.e. reversing the responses of the two patients with rightward torticollis appropriately). These two sets of statistical results were essentially the same and their presentation in the following refer to the normalized data, as if all our patients had a leftward torticollis.

Results

Psychophysical estimates

Normal subjects

With the body in primary position, the baseline VSA judgements of the normal subjects varied from –6.6° to 12.0°,

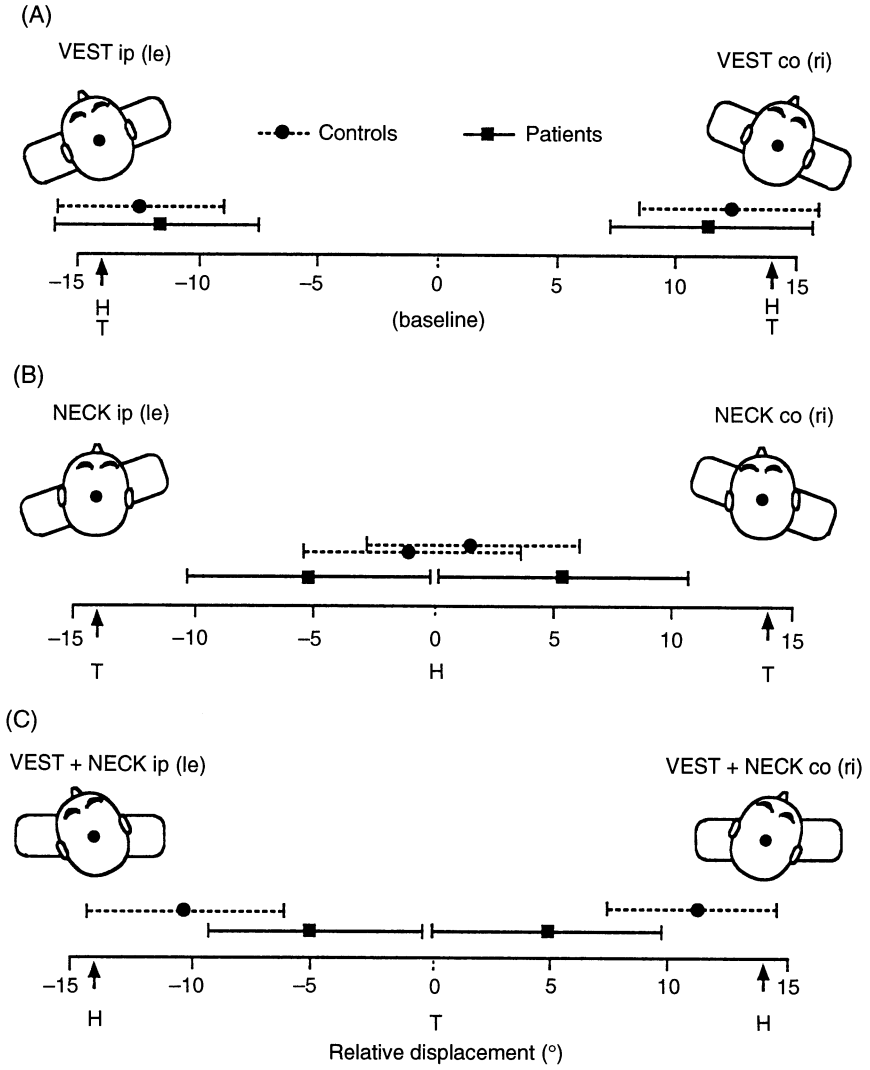

Fig. 2 VSA judgements in patients and control subjects following (**A**) vestibular (VEST), (**B**) neck (NECK) and (**C**) combined stimulation (VEST+NECK). Mean values (± SD) of responses are given relative to normalized baseline values, and across three stimulus durations. Stimulus direction is indicated with respect to torticollis direction in patients (ip = ipsilateral; co = contralateral) or to right (ri) or left (le) side in control subjects. Arrows indicate 14° displacements of head (H) and/or trunk (T) relative to primary position (see also pictograms).

but they were rather stable within each individual across the 18 trials (mean of SD values in individual normal subjects, ± 2.2°). On average, the VSA deviated from the body midsagittal plane by 1.8° (positive values, to the right). Precision of judgements within the probe stimulus sequences amounted to 1.1° on average (all normal subjects, all trials).

Their responses to the transient rotational stimuli are shown in Fig. 2 (relative to baseline, 0°). Following the VEST stimulus (14° whole-body displacement in space) to the right, the VSA was, on average, shifted by 12.5° to the right. Following the VEST stimulus to the left, the shift was –12.3°, i.e. to the left. With the NECK stimulus (trunk displacement under the stationary head) to the right and left, the VSA remained close to baseline, showing small shifts of 1.5° and –1.0°, respectively (Fig. 2B). Following the combined VEST+NECK stimulation (head displacement on the stationary trunk) to the right and left, there were VSA shifts similar to those with the VEST stimulus, amounting to 11.6° and –10.5°, respectively (Fig. 2C). Statistically, the shift magnitude with the VEST stimulus was independent of stimulus direction and duration (overall mean, 12.4 ± 3.6°), as was the case with NECK (1.2 ± 4.6°) and VEST+NECK (11.1 ± 4.7°) stimuli.

Note from Fig. 2A–C that the VSA of normal subjects corresponded roughly to their head midsagittal planes for all three stimuli. The deviations from the ideal head midsagittal plane (compare H in Fig. 2A–C) were –1.5° and 1.7° for the rightward and leftward VEST stimuli, respectively, 1.5° and

–1.0° for the corresponding NECK stimuli, and –2.4° and 3.5° for the VEST+NECK stimuli. Previous work suggested, and the present study confirms, that these deviations stem, at least in part, from a small post-stimulus shift of the VSA, which occurs during the response sequence and is oriented towards the primary body position in space with VEST stimuli, towards the trunk with NECK stimuli, and towards the trunk position (equal to primary head position in space) with combined VEST+NECK stimuli.

Patients

During testing, the patients' heads were not exactly in the primary position, but deviated by –6.0°, on average, in the direction of their torticollis (compare Methods section and Table 1). In this position, mean VSA baselines varied between 6.5° and –9.4° across the patients, averaging –0.2 ± 5.9°. Statistically, the baseline values for the patients were not significantly different from those for the normal subjects, and they did not correlate with the degree or direction of their head turns, either those at rest or those after the attempted correction during the experiment (Pearson $\rho = 0.07$ with $P = 0.84$, and $\rho = -0.1$ with $P = 0.97$, respectively). Furthermore, there were no statistically significant differences between patients and normal subjects with respect to intra-individual judgement variation and judgement precision.

Following VEST stimulation (whole-body displacement) in the direction of patients' torticollis, their VSA was shifted on average by –12.0° (i.e. in the direction of the stimulus; Fig 2A, left part). Following the corresponding contralateral stimulus, there was a shift of 11.3° (i.e. in the opposite direction). Following NECK stimulation (trunk-only displacement), there was a clear VSA shift away from the (stationary) head in the direction of the trunk displacement of –5.2° and 5.5° with leftward and rightward NECK stimulation, respectively. Following VEST+NECK stimulation (head-only displacement), the VSA was shifted by –5.0° and 4.9° in the direction of the head, a shift less than half as large as that seen with normal subjects. Statistically, shift magnitudes with VEST stimulation were independent of stimulus direction and duration (overall mean, 11.6 ± 3.9°), as were those after NECK (5.4 ± 5.4°) and VEST+NECK (5.0 ± 5.8°) stimulation. The differences from normal subjects were not due to post-stimulus VSA shifts, which were similar in both subject groups.

The data were treated by a $3 \times 3 \times 2 \times 2$ factorial ANOVA, with Stimulus Condition (VEST, NECK, VEST+NECK), Duration (20, 10 and 1.25 s) and Direction of stimulus (left versus right) as the within-subject repeated measures factors and Group (patients versus normal subjects) as the between-groups factor. On the whole, there was no difference between patients and normal subjects. Only the interaction of the factors Stimulus Condition and Group proved highly significant ($F = 9.41$, $P = 0.0004$), meaning that the VSA of the patients differed from that of the normal subjects, depending on the modality of the applied stimulus.

Head torque

Normal subjects

In the primary position, normal subjects exerted essentially no torque on the head holder. As to the stimulus-evoked torque responses, only the 1.25-s NECK stimulus was analysed in detail, since it gave the most reliable results. During this NECK stimulus, the torque rose to a peak value of 0.241 ± 0.127 N m (values for right and left stimuli lumped together, since there was no statistically significant difference). The peak of this dynamic response coincided approximately with the maximum of stimulus velocity. Yet, inter-individually it showed some jitter, so that the grand average of the torque curves gave a somewhat smaller peak value (Fig. 3). The dynamic response was followed by a static, slowly decaying response which amounted to 0.11 N m on average (measured 1.5 s after stimulus end).

Patients

Patients exerted considerable spontaneous torque in the direction of the torticollis (0.142 ± 0.159 N m); the difference from the normal subjects was highly significant ($P = 0.004$; factorial ANOVA). The patients' spontaneous torque values did not correlate with their VSA judgements. During the 1.25-s NECK stimulus, the dynamic response (peak torque values above prestimulus baseline) was larger for the leftward NECK (0.336 ± 0.235 N m) than for the rightward NECK stimulation (0.281 ± 0.176 N m; $P = 0.0013$), although this fact can hardly be appreciated from the grand average curves (Fig. 3). This asymmetry also applied to the static response (ipsilateral 0.19 N m; contralateral 0.13 N m). Overall, patients' dynamic and static responses were higher than those of the normal subjects, but the differences did not reach statistical significance.

Retrospectively, it was found that two normal subjects and two patients had actively helped the imposed head rotations with NECK and VEST+NECK stimulation, which clearly increased the variability of the torque data. However, when excluding these subjects from the statistical evaluation of the psychophysical data, this did not alter the significance of the findings. The same applied when we excluded these subjects from the analysis of torque presented above.

An additional observation was that the 1.25-s vestibular stimulus evoked a small transient biphasic response, with the initial component being opposite to the direction of rotation. It probably represents a response due to head inertia, but a contribution from a vestibulocollic reflex cannot be excluded. Noticeably, there was no statistically significant difference of response magnitude in relation to the direction of patients' torticollis, nor was there a significant difference between patients and normal subjects.

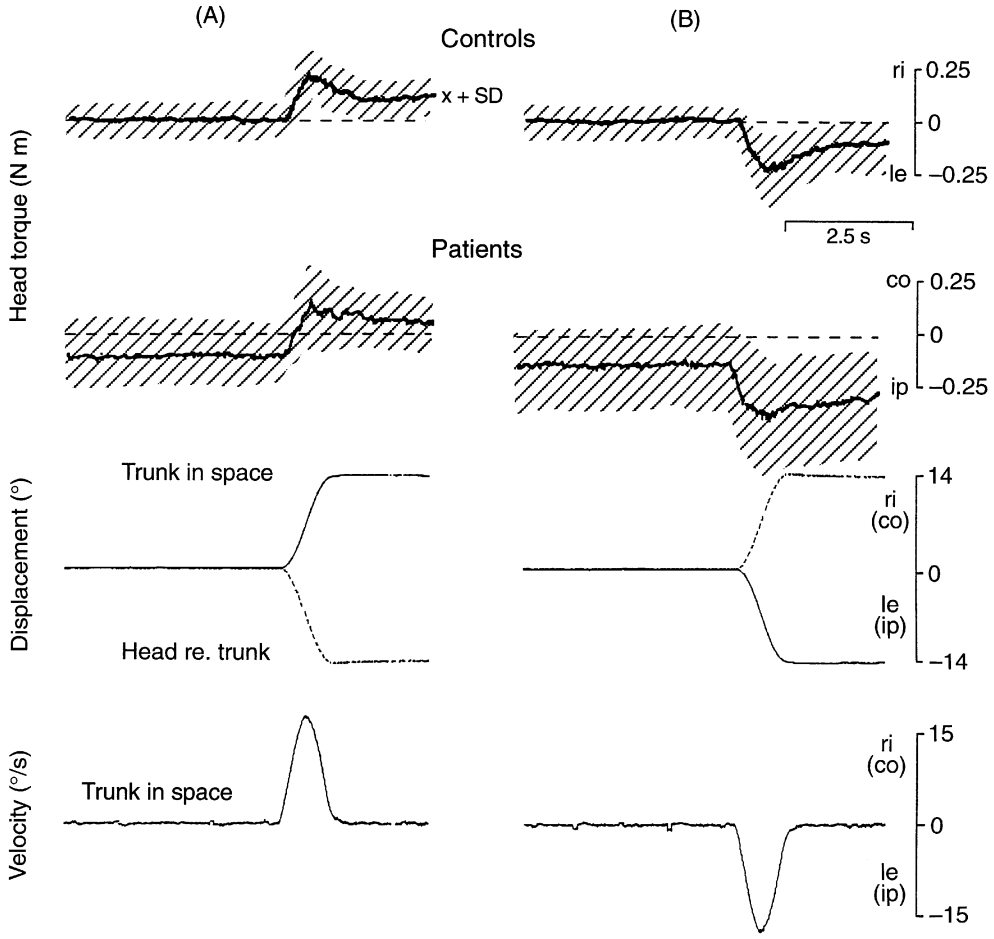

Fig. 3 Head torque of normal subjects and patients. Grand average torque curves (upper panels) obtained by combining responses obtained before, during and after NECK stimulation (1.25-s duration, 14° displacement) to right or left side in normal subjects (ri, le) and to the ipsilateral or contralateral side with respect to torticollis direction in patients (co, ip). Angular displacement and velocity curves below.

Normal subjects studied with the head misaligned with the trunk

After turning the head by 7° away from primary position, towards the right side in three normal subjects and towards the left side in three other normal subjects, we waited ~1 min before starting the test. After this time the initially raised head torque of the normal subjects had declined to ~0 N m. These normal subjects' baseline VSAs were shifted in the direction of the imposed head turn by 4.1°, on average, as compared with their baseline values obtained in the previous experiments in which their heads were aligned with their trunks. There was a statistically significant correlation between baseline values and head position (Pearson $\rho = 0.825$, $P = 0.04$). In contrast, their VSA responses to VEST, NECK, and VEST+NECK stimulation with respect to the new baseline were similar to those obtained in the previous experiments (statistically no significant difference). Furthermore, there were no major differences in the dynamic and static torque responses between the two experimental conditions (1.25-s NECK stimulus).

An additional experiment was performed to test whether the VSA is affected when normal subjects deliberately exert an isometric force against the head holder. We studied three normal subjects who were trained to produce a torque of ~1.5 N m during the VSA measurement procedure. This head torque produced no major shift in the VSA.

Eye movement measurements

In seven out of 10 patients, but in only one out of 12 normal subjects, a weak spontaneous nystagmus in the horizontal plane was recorded (Table 1). In six of the patients the slow phases beat in the direction of the torticollis, in the remaining patient in the opposite direction. However, the directional bias of the horizontal VOR exceeded the normal limits in only two out of 10 patients (mean 1 ± 10.1%). Displacement

gain of the patients' VOR to the transient stimulus (VEST 14°, 1.25 s) was in the normal range (0.91 ± 0.14). Frequent square wave jerks were recorded in four out of 10 patients.

Discussion

Are the functional systems that underlie orienting behaviour (Ventre *et al.*, 1984) imbalanced in torticollis patients? The symmetry of these systems was studied by means of VSA judgements. With the head and trunk in the starting position, patients' VSA directions showed considerable variation around the objective straight ahead (body midsagittal), but were similar to those of normal subjects. From this it appears that patients' VSAs are not displaced by the presumed asymmetry in afferent input due to the torticollis. Symmetry of VSA was also observed following vestibular and neck stimulation. However, there was a difference between patients and normal subjects which emerged after dissociating head and trunk positions; while the VSA in normal subjects coincided well with the head midsagittal plane, VSA in patients was considerably shifted from the head towards the trunk midsagittal plane. In the following we suggest two mechanisms to explain the findings in patients: (i) a central compensation, which restores symmetry of afferent inflow in patients; (ii) a reorganization of the egocentric reference for the VSA, by which it is shifted from the head towards the trunk.

Relevance of the psychophysical procedure

What is the physiological significance of the VSA? Judging the egocentric direction of a visual object as being straight ahead would mean that, subjectively, it is located neither left nor right from the perceived midsagittal plane of the body. Possibly, the VSA is somehow related to the subjective mirror symmetry of the body in a right and a left half, with the geometrical middle representing the origin ('null point') of the egocentric reference in its horizontal plane. There is a neuroanatomical basis for right and left hemispaces in the form of the crossed hemispherical representations of the body in the motor, oculomotor and somatosensory cortices as well as of the external world in the visual cortices of the right and left hemispheres. Yet, the functional organization cannot be related to this fact alone; in human subjects the right cerebral hemisphere appears to play the role of supervisor for spatial relationships with respect to the body and to objects in the external world. For instance, neglect symptomatology resulting from right hemispheric lesions is associated with ipsilateral deviations during pointing or gaze exploratory tasks (Heilman *et al.*, 1983; Mark and Heilman, 1990; Karnath, 1994; Karnath and Fetter, 1995).

In normal subjects VSA judgements in the dark with the head and trunk in the primary position are not absolutely precise, in that they are scattered around the body midsagittal plane, showing an idiosyncratic offset (Maurer *et al.*, 1997). When head and trunk orientations are dissociated from each other, the VSA then coincides well with the head rather than with the trunk midsagittal plane offset (Maurer *et al.*, 1997). This coupling to the head is not fixed, however, but appears to be related to the VSA task. For instance, a subject who was previously involved in a pointing task that required the trunk as a reference, may adhere to the trunk reference in a subsequently presented VSA task (Maurer *et al.*, 1997).

It is conceivable that the VSA task involves retinal and oculomotor inputs (Howard, 1982). The linkage between these inputs and the head is given by the fact that the head is the platform for the eyes. Functionally, the linkage is accounted for by a strong eye–head coupling in the form of vestibular and neck reflexes on the eyes and, at the perceptual level, a vestibular–neck interaction for motion perception and localization of visual objects (Mergner *et al.*, 1992; Maurer *et al.*, 1997). Under physiological conditions, the VSA remains aligned with the head midsagittal after vestibular and neck stimuli, whereas asymmetries of vestibular and neck inputs following acute lesions or during the application of nonphysiological stimuli (heat, muscle vibration) lead to a clear shift of the VSA (see Introduction).

Patients' psychophysical estimates

We explain the finding of a symmetrical VSA in our patients during baseline judgements and after application of the rotational stimuli by assuming that asymmetries of neck afferent inflow, associated with the long lasting deviations of the patients' heads, are compensated for by adaptive mechanisms. First, the patients baseline judgements will be considered. Typically, in spasmodic torticollis patients the head position is not fixed; the pathological head deviation fluctuates considerably throughout the day, depending on a number of factors (upright posture, emotions, voluntary innervation, antagonistic gestures, etc.). In our experiments, we fixed the patients' heads by means of a bite board and head holder, bringing them close to the primary position (i.e. from a deviation in the bite board of ~20°, at the time of the protractor measurements, to 6°, on average). Despite the facts that this represented a forced head position for the patients, and that it was not ideal in terms of a primary head-on-trunk position, their judgement precision and inter-subject variability of judgements (SD) was normal. Furthermore, their VSA judgements fell within the range of normal subjects (whose heads, however, were in the primary position; see also below), and no correlation was found between the judgements and the head deviation in the fixed or resting condition.

We were interested in learning how a manipulation of head position affects the VSA. When introducing an artificial long lasting head-on-trunk bias (7°) in six of our normal subjects, their VSA clearly shifted in the direction of the bias. This is in contrast to the patients, in whom the head manipulation had no comparable effect. As an explanation, we assume that VSA is not so closely coupled to the head in patients as in normal subjects (see below). It should be noted, however, that

there was a clear difference in the experimental conditions, in that normal subjects showed no major head torque with the head bias (only a transient torque towards the primary head position before we started the measurements), whereas patients produced a considerable torque away from their primary position in the direction of their torticollis. We deem it unlikely, however, that the head torque *per se* had a major effect on the VSA. One reason for this assumption is that there was no correlation between patients' head torque and their VSA judgements. A second reason is that voluntary production of an isometric head torque in normal subjects did not alter the VSA judgements.

The absence of a directional bias of the VSA baseline and our findings of symmetrical responses to the vestibular and neck stimuli could indicate either that asymmetries in neck afferent inflow are compensated at central levels, or that there is no such asymmetry. We favour the former hypothesis, which is suggested by the asymmetrical head posture, the asymmetrical torque associated with it, and the asymmetry of the dynamic torque responses during neck stimulation. As to the torque responses, they represent the sum of (i) spring forces of the muscles proportional to head-on-trunk displacement, (ii) viscous forces that are proportional to the velocity of displacement and (iii) a force exerted by the cervicocollic reflex. We do not know the relative contributions of the different forces to the responses, but we assume that their asymmetry is associated with an asymmetry of afferent inflow.

The abnormality in patients is that their VSA is not close to their head midsagittal plane, as in normal subjects, but is clearly shifted towards their trunks. Since head and trunk are interconnected by the neck, one might suspect an abnormality in the neck signal (e.g. very low gain). However, we have reason to believe otherwise. Preliminary data from our laboratory suggest that the patients' judgements of their head midsagittal and their trunk midsagittal planes, for which they used the same indication procedure as in the VSA task, are normal (i.e. approximately veridical). Furthermore, we must point out that adjusting the light spot to the head midsagittal does not require a neck signal; for this task it would suffice to zero the sum of the internal signals of spot-on-eye and eye-in-head (retinal and eye position signals). In contrast, the adjustment of the spot to the trunk midsagittal does require a neck signal; since the patients' subjective trunk midsagittal is veridical, the neck signal they use for this judgement must be 'correct' (gain close to unity for both sides). Therefore, our findings suggest that the central representations of these afferents are adequate, supporting the hypothesis that afferent input is not responsible for the asymmetry in motor output, i.e. the spasmodic torticollis.

We therefore assume that the shift of patients' VSA towards the trunk occurs at higher levels of processing, where an egocentric reference is created for the VSA. This mechanism may choose either the head or the trunk, for instance, as reference, depending on the behavioural task and other variables. Given that the head becomes an unreliable reference because of fluctuating involuntary head deviations as in spasmodic torticollis, it might be advantageous to use the trunk as a reference. This view would be in line with earlier studies. In a psychophysical study (Anastasopoulos *et al.*, 1997*a*, *b*), spasmodic torticollis patients were asked, while seated, to align a target line with the plane of facial symmetry. In this task, the spasmodic torticollis patients did not use a head coordinate system, as normal subjects do, but set the line almost vertical, i.e. in the direction of the long axis of their trunk. In a postural study (Lekhel *et al.*, 1997), neck vibration (which stimulates muscle spindles) was applied in standing spasmodic torticollis patients with abnormal head postures and in normal subjects who voluntarily tilted their heads. The postural responses in patients induced by neck vibration hardly depended on their head posture, whereas such a dependency was clearly present in normal subjects. This leads us to the notion of a symmetric abnormality in patients, which would be in line with a number of earlier observations in spasmodic torticollis and dystonia patients; symmetric abnormalities were found in psychophysical (Anastasopoulos *et al.*, 1997*a*, *b*), neurophysiological (Deuschl *et al.*, 1992; Mazzini *et al.*, 1994; Lekhel *et al.*, 1997), imaging (Schneider *et al.*, 1994) as well as cerebral blood flow studies (Tempel and Perlmutter, 1990).

It has been shown that the head direction is normally an important parameter for spatial navigation (see Grasso *et al.*, 1996). If spasmodic torticollis patients were to rely on their head direction during gait, for instance, they would deviate from the intended path direction. Conceivably, they circumvent this problem by relying less on their heads and more on their trunks during orienting behaviour.

We cannot completely exclude the possibility that our results are contaminated to some extent by the botulinum toxin injections our patients had received in the past, since the toxin is known to affect muscle spindle afferent discharges and result in intrafusal muscle fibre atrophy (Fillippi *et al.*, 1993; Rosales *et al.*, 1996). We exclude short-term effects, because our patients were always tested at least 3 months after the last injection. However, we cannot exclude long-term effects by botulinum toxin which are presently unknown. Notably, however, the one patient who had never had toxin injections showed essentially the same results as the other patients. Also the findings of normal spot adjustment to the trunk midsagittal (see above), which requires an accurate neck signal, is further evidence against a contamination of the results due to the toxin. Finally, patients treated with the toxin exhibit robust local neck responses to vibration (Lekhel *et al.*, 1997).

Eye movements

The finding of previous authors of a spontaneous nystagmus in a considerable proportion of spasmodic torticollis patients (Bronstein and Rudge, 1986) was challenged by other authors (Huygen *et al.*, 1989) who applied more conservative criteria (slow phase velocity of $>6°/s$). Six of our 10 patients showed

a weak nystagmus (slow phase <6°/ s) in the direction of their torticollis. It emerged only after some time in complete darkness. This may explain why it did not affect their VSA judgements. We deem it unlikely that the weak asymmetry in vestibular tone in spasmodic torticollis patients has any important functional consequences. This view is supported by our findings that the patients did not show much directional bias of their VOR, nor was there an asymmetry of VSA emerging after vestibular stimulation. The origin of the weak nystagmus remains open, to date. It appears not to be associated with an abnormal cervico-ocular reflex (Stell *et al.*, 1991) or tightly coupled with the abnormal head posture (Stell *et al.*, 1989). A vestibular hyperreactivity, as reported by others authors (Hyugen *et al.*, 1989), was not found in our patients.

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