PERCEPTION OF HORIZONTAL HEAD AND TRUNK ROTATION IN PATIENTS WITH LOSS OF VESTIBULAR FUNCTIONS

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Abstract—In patients with loss of vestibular functions, we studied psychophysically the self-motion perception for 'trunk in space' and 'head in space' during various combinations of horizontal head and trunk rotation in the dark. The results were compared to those of normal subjects. For their 'trunk in space' perception, the subjects relied on their internal image of space, derived from the vestibular receptors in the head, and referred their trunk to this as a reference by adding to it a nuchal trunk-to-head signal. The patients, by contrast, always considered the trunk as stationary. Obviously because they were devoid of any space cues, they abandoned or suppressed a neck contribution to their 'trunk in space' perception, which, in fact, would yield an erroneous perception in almost all conditions in the dark. Both the patients and the subjects based their 'head in space' perception on their internal representation of 'trunk in space' and added to this a nuchal head-to-trunk signal. However, the patients' head-to-trunk signal, unlike that of the subjects, was considerably larger than the actual head-to-trunk rotation at low stimulus frequency. We relate this finding to some unconscious modification of their neck muscle activity during passive head rotation. It appears that the patients' gain of the neck input per se is not increased, but rather that subsets of this input are modified according to the particular function they serve.

Keywords—self-motion perception; vestibular–neck interaction; spatial orientation; vestibular function loss.

Introduction

Spatial orientation is generally considered to rely on an interplay of several sensory cues. Among these the vestibular cues, provided by the labyrinths in the head, are thought to play an especially important role. Other cues stem from neck proprioceptors. They allow us to refer our trunk to the internal image of space derived from the vestibular input. How do patients with loss of vestibular functions use the neck input? Do they abandon or modify their use of the neck input? These questions led us to study the self-motion perception of such patients during vestibular, neck, and combined stimulations and to compare the results to those of normal controls.

If normal subjects when sitting in the dark on a rotation chair are presented with passive horizontal rotations of their bodies such that head and trunk are rotated independently of each other, they based their self-motion perception on combinations of vestibular (horizontal semicircular canal) and neck proprioceptive cues (1–3). More specifically, the subjects arrive at their perception of 'trunk in space' by summing linearly a nuchal trunk-to-head signal and a vestibular head-in-space signal. However, due to a relatively high 'velocity threshold' of these two signals, the resulting 'trunk in space' perception is erroneous (underestimated) at low angular velocities. This applies with one exception; since the vestibular and neck signals are of equal


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magnitude and have opposite signs during head rotation on stationary trunk, they cancel each other in this condition so that the trunk is veridically perceived as stationary, independently of the angular velocity of the head. The subjects' perception of 'head in space' is based on the just described internal representation of 'trunk in space,' to which they add a low-threshold nuchal head-to-trunk signal. (Thus, again, a correct perception is guaranteed only if the trunk is stationary.) In summary, the 'head in space' perception is referred, by the use of nuchal afferents, to a trunk coordinate system, which in its turn is referred to space coordinates that are provided by the sum of vestibular and neck signals (for details, see references 2 and 3).

What can be predicted from these findings in subjects for the self-motion perception of the patients in whom the vestibular input is missing? Conceivably, the use of only a neck signal for the 'trunk in space' perception would be disastrous; a head rotation would lead to the illusion that the trunk was rotated. One should therefore expect that the patients suppress this neck signal, thereby avoiding the possibility of a "false positive" trunk turning perception. On the other hand, their 'head in space' perception could well be based on the nuchal head-to-trunk signal, which subjects use in combination with their internal representation of 'trunk in space'; at least this neck signal would not lead to a "false positive" head turning perception with head rotation. These considerations led us to wonder what the patients' perception of 'trunk in space' and 'head in space' would be like during independent head and trunk rotations in the dark.

Methods

The experiments in patients were performed in parallel with a previously published study of subjects, using essentially the same experimental procedures (for details, see reference 3).

Apparatus

The experimental setup consisted of a turntable equipped with a chair in which to seat the subjects and with a head-to-trunk rotation device, to which a head holder with a bite-board was fixed. The axes of the two rotation devices were earth-vertically oriented and colinear with respect to each other and to the vertebral column of the patients/subjects, seated on the turntable.

Stimuli

Horizontal rotation of the turntable led to rotation of the patients'/subjects' trunk in space. Rotation of the table-mounted head holder led to rotation of their heads relative to their trunks, taken to represent the neck stimulus. Rotation of their heads in space resulted from the sum of the turntable and head holder rotations and represented the vestibular stimulus. The following stimulus conditions were used: 1) Vestibular stimulation. It was generated by turntable (whole-body) rotation. 2) Neck stimulation. It was generated by a head holder rotation combined with a counter-rotation of the turntable of same amplitude, thereby keeping the head stationary in space. 3) Various vestibular-neck stimulus combinations. These were generated by the appropriate combinations of turntable and head holder rotations (see below). The applied rotations were sinusoidal. Peak angular displacement, unless specified as otherwise, was $\pm 8^\circ = \text{constant}$. Larger and smaller displacements were introduced in sham trials during the course of the experiments in order to hide from the patients/subjects the constant amplitude paradigm. The following stimulus frequencies were used: 0.025, 0.05, 0.1, 0.2, and 0.4 Hz. The corresponding peak angular velocities (accelerations) were 1.3°, 2.5°, 5.0°, 10°, and 20°/s (0.03°, 0.2°, 0.8°, 3.2°, 12.6°, and 50°/s²). These velocity and acceleration values are of relevance if one considers that the different receptor systems we are dealing with have dif-
ferent transfer characteristics. The vestibular receptors in the semicircular canals, for instance, react to angular acceleration of the head in space as stimulus, whereas the corresponding canal afferents code essentially head velocity (see reference 4). The neck proprioceptive system, on the other hand, appears to code essentially velocity and position of the head-to-trunk excursion (5).

**Procedures**

Two different psychophysical methods were used in parallel experimental series in order to obtain measures of the patients' subjects' self-motion perception: a) *Magnitude estimations* (6; also 7). The patients/subjects estimated perceived peak-to-peak excursion of their trunk or head during the test trials (vestibular, neck, or combined stimulations in the dark) in relation to the peak-to-peak excursion of a visual object rotated about their stationary body during a preceding trial, ie, the "standard" ("cross-modality estimation"). Since this object motion perception has previously been found to be close to "truth" (8), the standard was considered to provide an almost "objective" scale. The estimates were normalized to a value of one and could be considered a rough equivalent of "gain" in conditions where they referred to an actual head or trunk rotation that equalled in magnitude the object motion during the standard trial. b) *Concurrent pointer indications.* In short, the patients/subjects, indicated the excursions of their heads in space by trying to keep a pointer continuously aligned with their head (trunk) and aiming with another pointer concurrently at an imagined stationary target far away in space. The potentiometer readings of the two pointers were recorded, taking the difference between them as a measure of the 'head in space' ('trunk in space') perception. In addition, each reading was analyzed separately; this allowed us to observe where the patients/subjects localized their heads (trunks) and space and to compare these indications with the objective measures.

**Patients**

They were drawn from a pool of 10 males and 4 females (aged between 18 and 30 years). Loss of vestibular function was suggested by absence of any considerable vestibulo-ocular reflex upon sudden deceleration after prolonged horizontal body rotation. The deficit of all patients was chronic and attributable either to meningitis in childhood \((n = 10)\), to section of both VIIIth nerves because of neurofibromatosis 2 years before the tests \((n = 1)\), to traumatic lesion of both VIIIth nerves one year before the tests \((n = 1)\), or to an unknown cause since birth \((n = 2)\).

**Perception of 'Trunk in Space'**

*Whole-body Rotation (Vestibular Stimulation in Subjects)*

Figure 1A shows the patients' median estimates as a function of stimulus frequency (6 patients, 8 estimates each; medians, interconnected by solid lines, and their 95% confidence intervals). For comparison, the estimates of an "ideal physical measuring device" are given as horizontal dashed lines. The patients' estimates were zero from 0.025 Hz stimulus frequency up to 0.2 Hz (indicating subjective trunk stationarity). Note from the confidence intervals that some patients did perceive the trunk as rotating at 0.2 Hz. However, these patients reported considerable uncertainty about the amplitude and direction of the perceived trunk rotation. At 0.4 Hz, all patients consistently perceived the trunk as rotating; their median estimate was close to that of the subjects (see below), although the confidence intervals betrayed a large data scatter (uncertainty with respect to the amount of turning).

The patients' oral reports on the source of this trunk turning perception, given on re-
quest retrospectively, also varied considerably. One patient reported that he perceived the self-motion by way of some air flow, two patients thought they had felt some shaking of the turntable, two other patients related it to some ill-defined “bodily feelings” in their trunk and extremities, while the remaining patient was totally uncertain about the origin (not unlike many subjects, by the way). Thus, it may appear that our patients received at 0.4 Hz some somatosensory self-motion cues. However, we cannot exclude the possibility that their self-motion perception also stemmed from some residual vestibular functions (in analogy to some residual hearing, which most of them disposed of). Small compensatory (slow) and larger anticompensatory (fast) eye movements were occasionally observed in some patients upon abrupt body deceleration; these could stem equally well from both, a residual vestibular input or some somatosensory input (for the possibility of a somatosensory induced nystagmus, see reference 9). Finally, we found no obvious difference between the self-motion estimates of the patient who had both VIIIth nerves cut because of neurofibromatosis and was completely deaf and those of the other patients.

Figure 1A also shows, for comparison, the subjects’ normalized estimates (medians interconnected by dashed lines; 6 subjects, 8 estimates each). Their median estimate was about 0.75 at the stimulus frequencies of 0.4 and 0.2 Hz. It attenuated considerably when frequency was lowered, reaching zero at 0.025 Hz (at this frequency, subjects considered the trunk as stationary). The decrement was essentially due to a “velocity threshold” of the perception of the order of 1°/s (compare reference 3; note that peak angular velocity decreased with decreasing frequency of the stimulus, since peak displacement was kept constant).

Neck Stimulation

The results are shown in Figure 1B. Remarkably, they closely resemble those obtained with vestibular stimulation (compare Figure 1A). In particular, the patients’ estimation curve was again zero from 0.025 to

![Figure 1](image-url)

Figure 1. The subjects’ and patients’ estimates of their ‘trunk in space’ perceptions (dashed and solid estimation curves, respectively) for vestibular stimulation (A), neck stimulation (B), and the vestibular-neck combination with rotation of their heads on stationary trunks (C). Sinusoidal rotations with peak angular displacement of ±8°. Medians of magnitude estimates (ψ) together with their 95% confidence intervals are plotted as a function of stimulus frequency. Dashed horizontal lines indicate the responses an “ideal measuring device” would deliver. The pictographs below each panel show schematically the stimulus conditions (top view of patient/subject; rotation of the trunk in space, TS, of the head in space, HS, and of the head on the trunk, HT).
Perception of Horizontal Head and Trunk Rotation

0.2 Hz, whereas it rose to about "normal" at 0.4 Hz. The trunk turning sensation at 0.4 Hz could possibly stem from neck input or from some other somatosensory self-motion cues.

And, once again, the curve of the subjects’ median estimates was somewhat below unity at high frequency and declined with decreasing frequency. Note the negative sign of the estimates; it indicates that the direction of perceived trunk turning corresponded to the actual trunk turning, but was related to the counter-phase head rotation relative to the trunk (i.e., the neck stimulus as defined above).

Vestibular–Neck Stimulus Combinations

Two experimental series were performed. In one series, the head was rotated about the stationary trunk (in-phase vestibular–neck combination), applying the stimulus frequencies given above. As shown in Figure 1C, the patients’ estimates of ‘trunk in space’ were zero without exception (patients only perceived a head turning; see below). Given that their ‘trunk in space’ perception at 0.4 Hz with whole-body rotation (Figure 1A) was due to some residual vestibular functions, one could speculate that it was canceled by summation with its matching nuchal counterpart (Figure 1B) during the head rotation. Alternatively, the patients may have relied on somatosensory self-motion cues from the trunk, which was stationary with this combination.

Also the subjects perceived the trunk as stationary across all frequencies tested (mean estimates were zero). Note that this perception was veridical, and that there was no data scatter (confidence intervals were zero). These findings have been taken to reflect: a) a mutual cancellation of the vestibular and neck inputs, and b) a relatively high detection threshold of this perception, which yields a zero output even if the cancellation is not complete (3).

In a second series, five different stimulus combinations were presented (head rotation in space, the vestibular stimulus, was always ±16°; head-to-trunk rotation, the neck stimulus, was varied in its amplitude and in its phase relation to the vestibular stimulus; trunk rotation in space varied between 0 and ±16°). This series was presented twice, once at 0.2 Hz and the other time at 0.05 Hz. The patients’ estimates (not shown) were zero with all combinations at the two frequencies tested. The subjects’ estimates of ‘trunk in space’ (not shown) varied as a function of the neck stimulus in the combination and were proportional to the actual trunk rotation. Once again, these findings were taken to support the view that vestibular and neck inputs are summed linearly.

Perception of ‘Head in Space’

Whole-Body Rotation (Vestibular Stimulation)

Both the subjects’ and the patients’ estimates (not shown) were essentially identical to those they had previously delivered for their ‘trunk in space’ perception (compare Figure 1A).

Neck Stimulation

The patients experienced a head rotation in space despite the fact that their heads were kept stationary (Figure 2A). At 0.4 Hz stimulus frequency, the magnitude and direction of this illusion corresponded roughly to the head-to-trunk excursion. The magnitude showed a considerable increase with decreasing frequency. Also, the subjects estimated an illusory head rotation in space. This illusion was small at high stimulus frequencies and increased considerably with decreasing frequency. Its direction also corresponded to the head-to-trunk excursion.

It appears as if patients, deprived of any space cues in our experimental conditions, relied on their trunks as stationary references and used nuchal head-to-trunk signals for their ‘head in space’ perceptions. Evidence for this assumption was found when we presented them with the same neck stimuli and
asked them to give estimates of their 'head to trunk' perception. The results are shown in Figure 2B; the patients' estimates of 'head-to-trunk' rotation closely resembled those they previously had given for their 'head in space' perception.

Subjects, by contrast, underestimated somewhat the head-to-trunk rotation, and their estimates remained essentially constant over frequencies (Figure 2B). Thus, interestingly, depending on which self-motion perception the subjects estimated, the same neck stimulation yielded three clearly different estimation curves; the one of 'trunk in space' showed a decrement (Figure 1B), that of 'head in space' an increment (Figure 2A), and that of 'head to trunk' (Figure 2B) an almost constant level with decreasing frequency.

Vestibular-Neck Stimulus Combinations

In the series of experiments with head rotation about the stationary trunk (in-phase vestibular-neck combination), the patients again overestimated the turning of their heads in space; their median estimate was close to "ideal" at 0.4 Hz, but it increased with decreasing frequency and was almost double at 0.025 Hz (Figure 2C). Their estimates roughly resembled the ones they had previously given with neck stimulation alone for the 'head in space' and the 'head to trunk' perception (Figures 2A and 2B, respectively), which would fit the assumption that their perception was determined essentially by the nuchal head-to-trunk signal alone with any of the three curves. Note, however, that the increment with the combined stimulation was somewhat larger than that obtained with the neck stimulation alone. A possible explanation is that the patients received some head turning cues from the head rotation motor during the combined stimulation (eg, by vibrations), but not from the turntable motor as during the neck stimulation.

In contrast, subjects underestimated slightly the rotation of their heads (Figure 2C). But their estimates were almost constant over frequency, so that this perception was closer to "veridical" than their estimates of vestibular stimuli with their decrements at low frequencies (Figure 1A). How does one interpret this improvement of the subjects' 'head in space' perception?
Perception of Horizontal Head and Trunk Rotation

We could show, with the help of the pointer indication procedure, that they based their perceptions on subjective trunk stationarity (Figure 1C), to which they added the nuchal head-to-trunk signal (Figure 2B), thereby rejecting the alternative interpretation that the estimation curve in Figure 2A reflected a genuine neck signal of ‘head in space,’ which the subjects used to compensate for the difference between the vestibular and the ‘ideal’ perception in Figure 1A (see reference 3).

In the series of vestibular-neck combinations with always the same vestibular stimulus and various neck stimuli (see above), the patients’ estimates (not shown) again appeared to be solely determined by the neck stimulus in the combination. The subjects’ ‘head in space’ estimates (not shown) revealed again a monotonic dependence on the neck stimulus in the combinations, which we took as further evidence of a linear summation of the vestibular and neck effects involved.

Concurrent Pointer Indications

These indications provided us not only with a measure of perception magnitude, but also with the temporal aspects of the stimulus–response relationship (the phase). The results obtained for the ‘head in space’ and ‘trunk in space’ perception were qualitatively similar to those described above for the magnitude estimation in both the patients and the subjects. Therefore, only a few details from the patients will be considered here. The magnitude of their ‘head in space’ indications, again determined essentially by the neck stimulus alone in all stimulus conditions, was close to “ideal” at 0.4 Hz and increased with decreasing frequency (compare above). Despite this frequency dependency, the phase was close to “ideal” (about zero with respect to the head rotation) across all frequencies tested. On separate analysis of the pointers for the head and space (see Methods), it was found that the patients always kept the space pointer aligned with their trunks (which they obviously took as stationary references) and only moved the head pointer. Thus, it was their subjective localizations of their heads relative to their trunks that determined their ‘head in space’ perceptions and was overestimated at low frequency.

However, the increment of response magnitude with decreasing frequency was somewhat less with the pointer indication as compared to the magnitude estimation. We suspect that the pointers provided the patients with some faint “space cues.” Evidence for this assumption was obtained by additional experiments; the patients’ indications became approximately “normal” (i.e., they no longer showed the pronounced increment at low frequency) when we allowed them to touch with their hands (feet) a ground-fixed handle (the ground). A further finding with this space reference was that the patients perceived the trunk, in addition to the head, as turning in space, a perception that was supplied by proprioceptive cues from the limbs.

Discussion

The patients, when presented in the dark with combinations of trunk and head rotations, were not completely disoriented, but perceived their trunks as stationary and their heads as moving in space. This was similar to the normal subjects when stimulus magnitude was below detection threshold of their ‘trunk in space’ perceptions (at 0.025 Hz; ±8°). On the other hand, at stimulus frequencies of 0.4 Hz (or higher, as tested occasionally), the patients did perceive the trunk turning (due to either residual vestibular functions or somatosensory cues), which again was similar to the subjects. Thus, at stimulus frequencies of <0.05 Hz and >0.2 Hz the patients’ self-motion perceptions essentially corresponded to those of the subjects.

The patients and subjects differed from each other, however, in the frequency range of 0.05 to 0.2 Hz. Thus it appears that, in this frequency range, the canal system is indispensable for any “inertia navigation” of the body in space. This applies especially for the perception of ‘trunk in space.’ The subjects relied on their internal image of space, derived from the vestibular receptors in the
head, and referred their trunks to this as a reference by adding to it a nuchal trunk-to-head signal. The patients, by contrast, always considered the trunk as stationary, obviously because they were devoid of any space cues. They apparently abandoned or suppressed a neck contribution to their ‘trunk in space’ perceptions, which, in fact, would yield an erroneous perception in almost all conditions in the dark. However, as will be detailed in a later publication, the patients do dispose of such a nuchal trunk-to-head signal in the presence of visual or somatosensory space cues. For instance, they perceive the trunk as rotating in space if they are presented, during trunk rotation about the stationary head, with a head-fixed (= stationary) visual scene.

Both the patients and the subjects based their ‘head in space’ perception on their internal representations of ‘trunk in space’ and added to this a nuchal head-to-trunk signal. Unexpectedly, the patients’ head-to-trunk signals, unlike those of the subjects, were considerably larger than the actual head-to-trunk rotations at low frequency (they did become “normal,” however, if they were provided with somatosensory or visual space cues). So far, we have no explanation for the patients’ exaggerated head-to-trunk signals. Yet, we suspect that these are related to some unconscious modification of neck muscle activity. When we measured the head torque in some of the experiments, we found it to be larger in the patients than in the subjects and, unlike in subjects, to clearly lead the head rotation in phase (again, the torque became about “normal” if space cues were presented). By contrast, detection thresholds for the head-to-trunk displacement, which we also tested, were about the same in the patients and subjects (± 0.2°).

Possibly, there is an analogy of the exaggerated head-to-trunk signals of the patients as compared to the subjects in their oculomotor response to neck stimulation. Only a very weak cervico-ocular reflex (COR) has been found in subjects (10), whereas a COR with considerable amplitude has been observed in some patients with loss of vestibular functions (11,12,13). Such an analogy should be considered with caution, however, since our findings clearly suggest that in the patients the gain of the neck input per se is not increased, but rather that subsets of this input are modified according to the particular function they serve.

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**REFERENCES**


