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AN ANALYSIS OF OCULAR COUNTERROLLING IN RESPONSE TO BODY POSITIONS IN THREE-DIMENSIONAL SPACE

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□ Abstract—Four normal subjects underwent ocular counterrolling testing in a tiltable chair. Measurements were taken in 62 different body positions in steps of 30° varied rolls and pitches. In each body position the eyes were recorded on video and their roll angle was determined automatically by computer analysis. The ocular counterrolling profile showed a periodic characteristic with maximal amplitude at roll tilts of 60°. In this study we can clearly show that the eyes' rolling response is not systematically affected when lateral body tilts are combined with any tilts in the pitch direction. This undoubtedly implies that the ocular counterrolling was mainly stimulated by the subject's roll angle. As an empirical contribution, this study provides new data specially to be used in modelling and simulating the function of otolith organs.

□ Keywords—ocular counterrolling; 3D space; pitch; roll; tilt.

Introduction

Tilting the head sideways causes ocular counterrolling (OCR), a rotation of the eyes around their sagittal axes. OCR is mediated by the stimulation of the otolith organs in the inner ear (1,2). The otolith receptors respond to shear forces acting on their hair cells. The degree to which the eyes rotate is of crucial importance for investigations in spatial perception for at least two reasons:

A) To determine the precise coordinates of physical objects on the retina as the head is tilted sideways, the angular alignment

of subject's eye must be known with reference to gravity. Since this angle exactly differs by the extent of OCR angle from subject's head position, the rotation of the retinal image about the vertical eye axis is obtained by subtracting the OCR from the head tilt (this simplified calculation is true for head tilts in pure roll direction at least).

B) Since OCR is mediated by the utricles (2), it can be considered as a behavioral correlate of otolith function. It therefore allows an additional access to the study of afferent vestibular information that is involved in postural adjustments and perceptive mechanisms.

In order to perceive physical objects oriented in space as they really are, OCR would be a conceivable type of compensation. However, since maximal OCR hardly exceeds 10° in humans, it does not fully compensate lateral tilts and therefore does not lead to a positional constancy of the retinal stimulus pattern. Influences of body tilts on the retinal image are compensated by central-nervous processes. Investigations concerning the problem of the subjective vertical deal with such compensatory mechanisms (3-13).

OCR is often used as a reliable indicator for labyrinthine disturbances (14) and recently OCR has been convincingly shown to be a most reliable predictor of susceptibility to space motion sickness (15,16). In addition, the knowledge of the OCR response in vari-

ous positions of the otolith organs with respect to gravity provides information about the central-nervous processing of afferent utricular signals. By computer simulation modeling of the response of utricular haircells (17), the present data can be compared to the simulation results to validate proposed neural network models (see also [18]). In this sense, this investigation can be regarded as an empirical contribution to the function of OCR. The rationale for this study is to observe the OCR not only in the positions where it is most likely to occur (pure roll positions), but in a variety of different body positions. These tested positions are distributed equally over an imaginary sphere. Relative to the previous studies mentioned above, we took measurements in a large number of *combined* pitch and roll body positions yielding a more complete spatial OCR pattern.

Methods

Apparatus

Our apparatus allowed us to tilt human subjects into every desired body position relative to gravity (see Figure 1). The cockpit in which the subjects were placed could be turned forward and backward in order to vary the pitch dimension. By turning the whole frame in which the cockpit is suspended, we were able to tilt the subject sideways, thus varying the roll dimension. Both possible movements could be performed independently as well as in combination.

To reduce extra-otolith postural influence on the perception of the vertical (which also was measured during these experiments), the subject was placed in a seat surrounded by inflatable pillows. By inflating the many different sections individually, we ensured that the subject remained in a fixed position while still feeling comfortable as this afforded a better distribution of the pressure that he or she experienced. (For more details about the space perception in our experiments and discussion on somatosensory influences see references 19 and 20). Stabilized by a removable bite-board, the subject looked through binoculars. An onboard camera, equipped with a macro optical lens and connected to a video system, was used to monitor each eye independently. Both eyes remained fixed on a target point, which was displayed by a mirror system in the optical axis of the camera. In order for the eye to be monitored on the screen, an infrared light diode was directed toward the eyeball. To avoid out of focus recording, the lens could be adjusted by remote control while the experiment was in progress. These pictures were videotaped for further computer analysis. For matters of subjects' convenience and therefore reliability reasons, this noninvasive OCR measuring procedure is to be preferred over others, as, for example, the scleral coil technique, especially in studies that include perceptual tasks.

Analysis

Single frames were analyzed by image analysis of the iris pattern. The OCR angle was

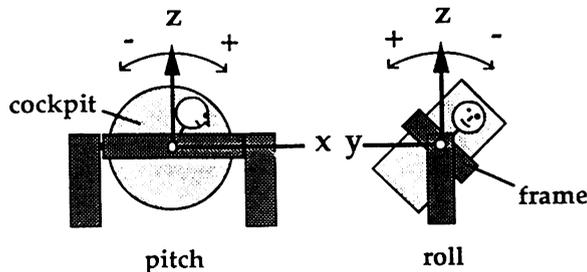


Figure 1. The apparatus used to tilt the subject into every possible body position. By turning the cockpit around the y-axis, the pitch angle is varied. By changing the position of the whole frame around the x-axis, in which the cockpit is suspended, the roll angle is varied.

calculated by comparing the recorded frames with reference frames taken previously in a separate session in upright body position (0° tilt). This iris pattern was scanned in concentric circles around the pupil center. The sequence of the grey values on the scan circles of the two frames was approximately the same. They differed mainly in rotational position. The extent of this phase difference can be determined by crosscorrelation, and this value represents the angle of OCR. A mean of 10 different OCR values of both eyes was taken. The standard errors reflect the variation of OCR values obtained from the video recording (10 seconds) taken at each body position. A complete description of this procedure is given elsewhere (21). A similar one is used by Clarke and colleagues (22).

Experimental Setting

In the present study, the OCR angle was measured in combined pitch and roll body positions. In steps of 30°, pitch was varied from -60° to +90°, and roll from -180° to +180°

(see Figure 2). In each session, lasting approximately 50 minutes, subjects were brought into 6 different, randomly selected body positions. The starting point for each tested position was the upright body position. This periodical resetting of the starting point allowed us to rule out possible hysteresis effects (5,12). About 5 minutes later, after subjects finished performing their perceptual tasks, one eye after the other eye was recorded on videotape for 10 seconds (about 250 available single frames). During this time, no visual stimulus that could possibly provide a directional cue was presented, in order to avoid visually induced OCR (23). The resultant data consisted of OCR angles measured in 62 different body positions. Four subjects took part in our experiments: two females (F1, F2) and two males (M1, M2), between 22 and 26 years of age. Their state of health was checked by standard medical testing.

Results

The data were quantified at each of the 62 measurement points by calculating the mean

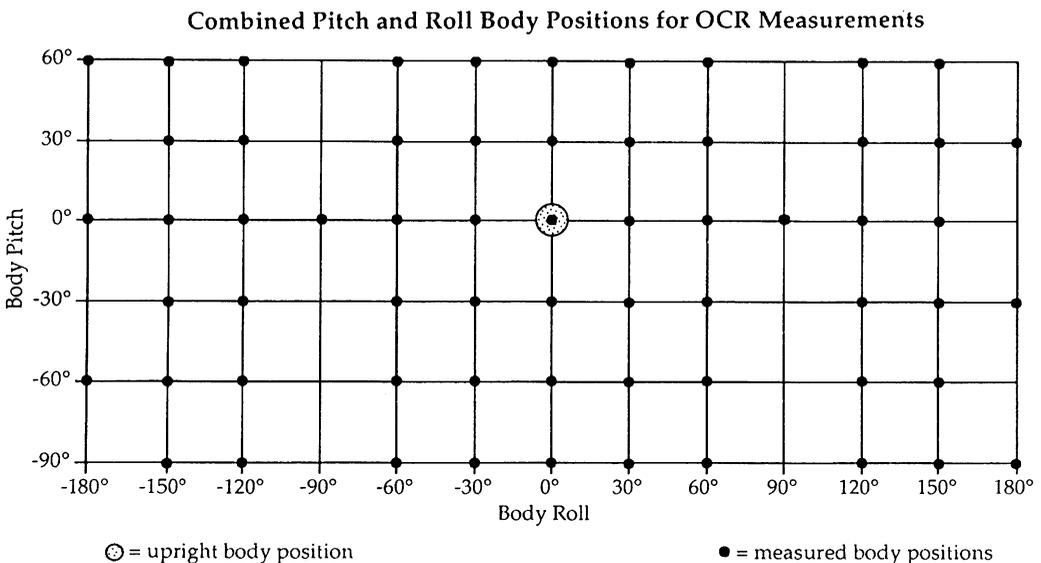


Figure 2. We have measured OCR at 62 different locations on the sphere. All of these pitch/roll combinations are indicated here with black dots. Along the vertical gridlines at roll -90° and roll 90° you find only one dot, since changing the pitch angle at 90° roll does not affect the direction of the gravitational vector relative to the otolith organs.

value of 10 different video frames of each eye separately. Amplitudinal differences of the two eyes were present but not further examined in this study. The OCR profile obtained for each subject is shown in Figures 3a through 3d. The standard error at each displayed data point (mean of 2×10 values) was $\leq 0.6^\circ$. The different combined pitch and roll tilts are displayed on the base plane. The degrees of OCR are represented by the curved surface. In body tilts to the right (positive roll), the eyes rotate to the left (negative OCR values), and vice versa. Following the roll angle from -180° to 180° , the curves show a periodic characteristic mainly irrespective of pitch. The OCR strongly increases as body tilt approaches a roll angle of -90° and -60° (left ear down) and 60° and 90° (right ear down). The maximal amplitude of the OCR of each of the 4 subjects is shown in (Table 1). The amplitude varied from 8.3° (F1) to 10° (F2) in body tilts to the left (negative roll) and -5.7° (F1) to -10.5° (M1) in body tilts to the right (positive roll). The extreme values were found in positions where the roll angle was $\pm 60^\circ$. However, the maximal amplitude is found in a *combination* with a pitch angle, the only exception being subject F2. OCR differences when subjects were tilted to the right or to the left (see Figures 3a through 3d, Table 1) demonstrate an asymmetric continuation of the OCR. Most asymmetry occurred in subject F1 (maximal absolute values 8.3° left ear down,

5.7° right ear down). However, such tendencies were not found in all subjects, for example, subject M2. It can also be seen that the sinusoidal characteristic of the OCR was not much affected when a roll angle was combined with a pitch angle from -60° to $+90^\circ$. This means that following the grid line in the graphs at any given roll angle along the various pitch angles shows no remarkable changes in elevation. It is seen clearly when overlaying the different pitch series in a 2D graph, as is shown in Figures 4a through 4d, that OCR is not systematically affected if lateral body tilts are combined with any tilts in the pitch direction. Kendall's rank correlation did not show any statistically significant changes (at 1% probability level) of OCR with varied pitch at any measured roll angle. Only moderate OCR values ($< 2^\circ$) could be observed in pitch-only tilts.

Discussion

The general characteristic OCR response agrees with what was shown in earlier studies (2,4,5,9,13,14,21,24). With an increasing roll angle of the body position, OCR increases to reach its maximum at a body roll between 60° and 90° . The amplitude of OCR shows some asymmetries between left and right body tilts. In the present study, we report OCR measurements obtained at different body positions, most of them being *combined* pitch and roll positions.

The reason for asymmetric OCR values, obtained when subjects were tilted to the left and right, may be due to intra-individual differences in the anatomy of the otolith organs (25–28). The observed asymmetry of OCR could represent a behavioral correlate of asymmetric *positioning* of the otoliths in a stereotactic coordinate frame of the head. In addition, the fact that most OCR peaks occur in *combined* pitch and roll tilts (roll always 60° and -60° , see Table 1) may also be due to anatomical positioning parameters.

We have clearly shown that the OCR values mainly depend on the roll angle of the body tilt. The same sinusoidal characteristic that has been demonstrated in pure roll exper-

Table 1. The body positions (pitch and roll) in which the maximal absolute OCR angles occur (the data for tilts to the left and to the right are presented separately)

Subject	Side	Absolute max. OCR angle	Pitch	Roll
F1	left	10.0°	-60	-60
	right	8.6°	0	60
F2	left	8.3°	30	-60
	right	5.7°	90	60
M1	left	9.4°	-60	-60
	right	9.2°	-30	60
M2	left	9.5°	30	60
	right	10.5°	30	-60

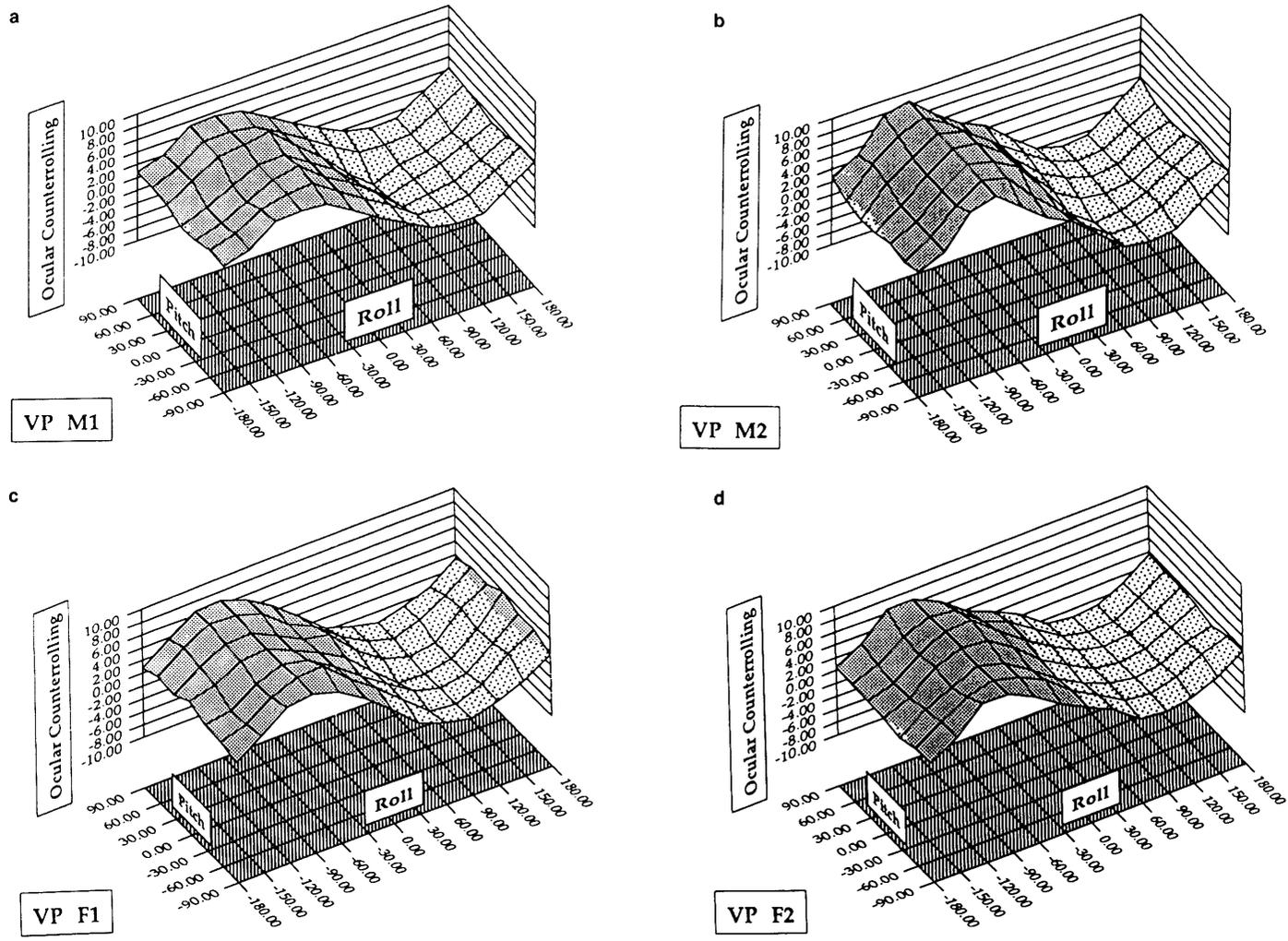


Figure 3. The figures 3a-d show the OCR angles of each subject in all measured body positions. The grey patterns split the curved surface into negative and positive OCR values, depending on the side of body tilt.

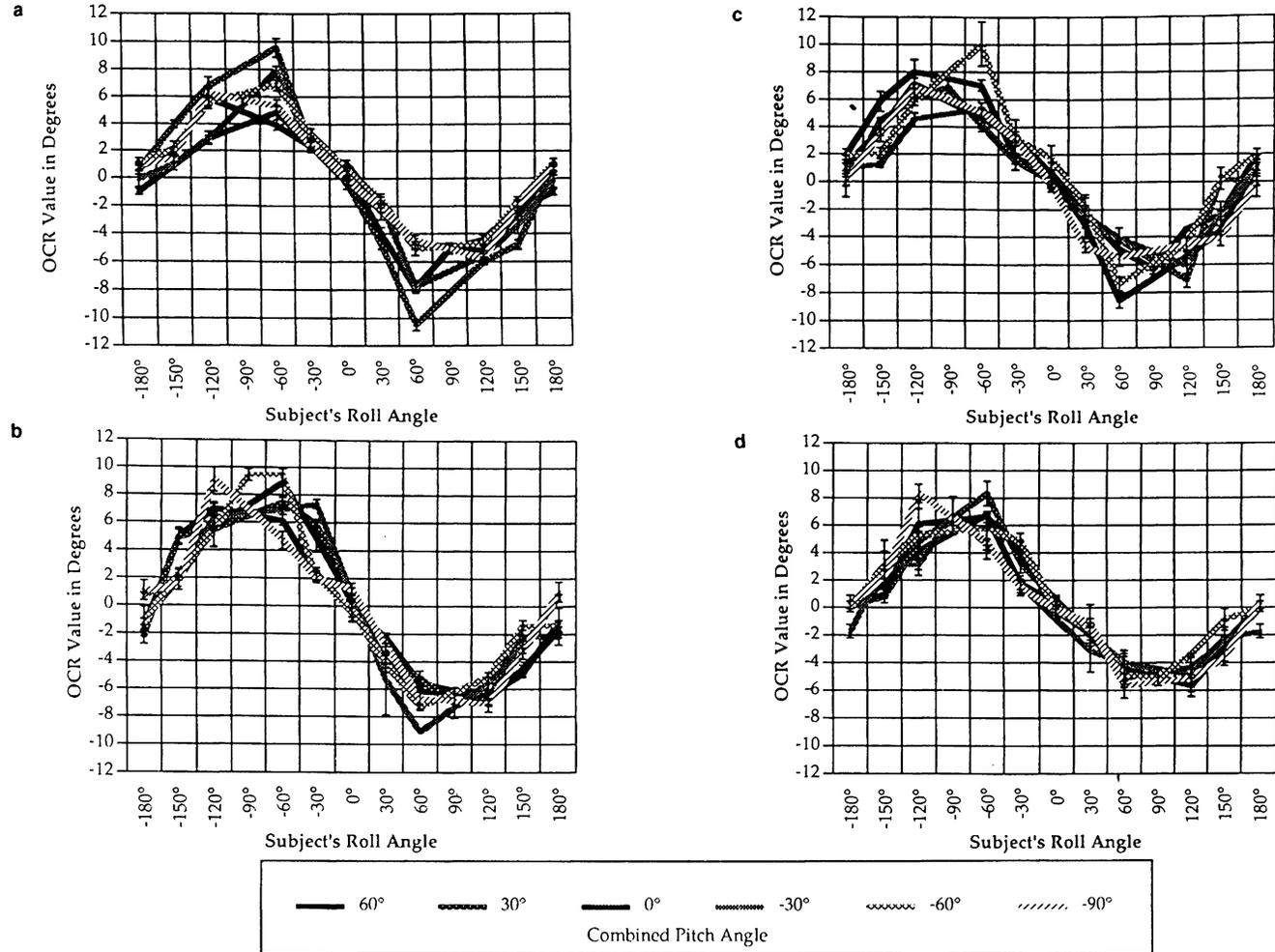


Figure 4. Figures 4a through 4d show each subject's OCR response at different attitudes. Each curve shows a specific combined pitch angle between +60° and -90°. The error bars reflect the standard errors resulting from the multiple OCR measurements taken from the 10-second video tape recording at each body position.

iments has also been shown in measurements taken in *combined* pitch and roll positions, for example, the barbecue rotation, pitch: -90° , roll: -180° to 180° (see also references 14 and 29). In contrast to that, from an engineering point of view, we would have to design an external compensatory mechanism (for example, for a camera) that would be dependent on the roll *and* the pitch angle. This is true even if we only want to compensate for a tilt which keeps the projection of the gravitational vector vertical on the xy plane of the camera.

Considering the OCR response in combined pitch and roll positions, our data support that "we can be reasonably sure the utricle is the primary sensory organ" (reference 27, p. 265). Although the saccule can be expected to be most sensitive to pitch tilts, it hardly contributes in an exhibitory manner to the afferent otolith signals mediating OCR.

A computer simulation of the otolith response to head tilts shows that the utricular stimulus patterns in roll positions vary when combined with different pitch tilts (17,30). Therefore, we assume that the afferent utricular signals contributing to the OCR must be processed in a way that a pitch-independent OCR response is mediated. This may demonstrate how necessary it is to observe mechanisms as OCR also in situations where they are not expected to contribute in functional terms.

Although moderate, OCR values could be found also in all subjects in pure pitch positions, which are difficult to explain in functional terms. Considering the amplitude and the variation, it may rather be attributed to a temporal fluctuation as also shown by Miller (31).

In general terms, neither our present study nor any previous studies to our knowledge have been able to support a compelling biological function of OCR. Space constancy in humans is achieved by more complex internal compensatory processes. Despite its ineffectiveness as a compensatory mechanism, it can be concluded from these data (providing systematic measurements in combined pitch and roll positions) that the OCR is a very useful tool for further investigation of otolith function and its underlying netting in an alternative access than is used for example, in neurophysiology or neurobiology.

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