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Arthrokinetic Nystagmus and Ego-motion Sensation*

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Summary. A compelling illusion of body rotation and nystagmus can be induced when the horizontally extended arm of a stationary subject is passively rotated about a vertical axis in the shoulder joint.

Lateral nystagmus with the fast phase beating in the opposite direction to the arm movement was found consistently; the mean slow phase velocity increased with increasing actual arm velocity and reached about 15°/sec; the mean position of the eyes was deviated towards the fast phase as in optokinetic nystagmus, and the nystagmus continued after the cessation of stimulation (arthrokinetic after-nystagmus).

The existence of an arthrokinetic circularvection and nystagmus indicates a convergence of vestibular and somatosensory afferents from joint receptors. It is concluded that information about joint movements plays an important role within the multisensory processes of self-motion perception.

Key words: Arm movement – Joint receptors – Nystagmus – Circularvection – Man

The perception of passive body motion mainly relies on vestibular and visual information; little is known about the contribution of somatosensory cues.

Active movements of the limbs are involved in locomotion and postural balance as well as voluntary grasping and manual tasks in which the spatial localization of touched objects is usually performed in egocentric coordinates. This means that the reference system of arm position and arm movement is anchored to a seemingly stationary body and that relative localization is determined by six subjective directions: right, left, upward, downward, forward and backward.

At least in animals "arm" movements may also serve locomotion thereby possibly providing feedback information about body rotation or translation correspondingly. Indeed, passive rotation of one arm in the shoulder joint may also in man produce a compelling illusion of self-rotation in the opposite direction. In this instance the origin of the stationary reference system is transferred to the point of the hand contact. Exteroceptive ego-orientation therefore is involved in the feedback control of locomotion and postural stabilization also in man.

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Thus, somatosensory information deriving from joint receptors (comparable to the visual system) allows for two perceptual interpretations: either limb movement or self-movement. If so, one may then hypothesize a somatosensory-vestibular convergence within the vestibular nuclei. An analogous convergence of exteroceptive information has been demonstrated for the visual and the vestibular systems (Dichgans and Brandt, 1977). Since the perception of self-rotation is usually accompanied by nystagmic eye movements one should also expect an arthrokinetic nystagmus.

The following experiments prove the existence of a purely somatosensory or joint induced nystagmus and the sensation of ego-motion (circularvection).

Methods

Subjects

Twenty healthy subjects (13 males; 7 females) ranging between 20 and 45 years of age took part in the experiments. Three of these were the authors; the seventeen other subjects were previously unfamiliar with the phenomena being investigated. Nineteen of the subjects had no spontaneous nystagmus; one exhibited a slight physiological spontaneous nystagmus to the right and a directional preponderance to rotational stimuli.

Apparatus

Subjects sat on a rotatable chair located at the center of a closed cylindrical drum, 1.5 m in diameter, whose inner walls were painted with alternating black and white stripes each subtending a 7° visual angle. The illumination within the drum cabin was controlled by the experimentor from outside. Both the chair and the drum could be rotated independently at controlled accelerations or constant angular velocities. The subject's head was restrained with a head holder (Tönnies, Freiburg). Part of the experiments were performed with a simple rotating chair as used for clinical electronystagmography (Tönnies, Freiburg).

Recordings

Horizontal and vertical components of eye movements were separately recorded by means of electro-oculography (Jung, 1953) using Beckmann-electrodes. After DC-amplification they were displayed on a stripchart recorder. In the experiments with repeated arm movements at different stimulus velocities (Fig. 3) eye movements were recorded with AC-amplification and a time constant of 10 sec.

In some experiments subjects were required to continuously indicate their self-motion sensation (circularvection) by turning a potentiometer according to the magnitude of apparent angular velocity (magnitude estimations, Stevens, 1957). The standard reference stimulus was a 10°/sec chair-rotation, given once at the beginning of the experiment.

Experimental Procedure

a) *Optokinetic nystagmus* (OKN) and optokinetic after-nystagmus (OKAN) were induced by drum rotation at constant angular speed (10°/sec) either to the right or to the left. The 10 sec periods of stimulation were terminated by turning off the lights while the eye-movements were continuously recorded with the eyes open.

b) *Vestibular nystagmus* was induced by angular acceleration of $2°/sec^2$ for 5 sec about the subject's vertical Z-axis with the eyes open in complete darkness.

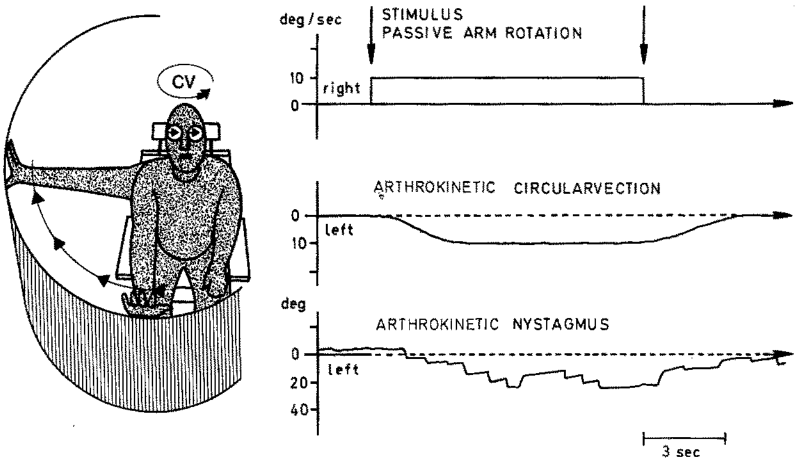

Fig. 1. Schematical drawing of the stimulus condition (left) and an exemplary original recording of arthrokinetic circularvection and nystagmus (right) induced by passive rotation of the arm

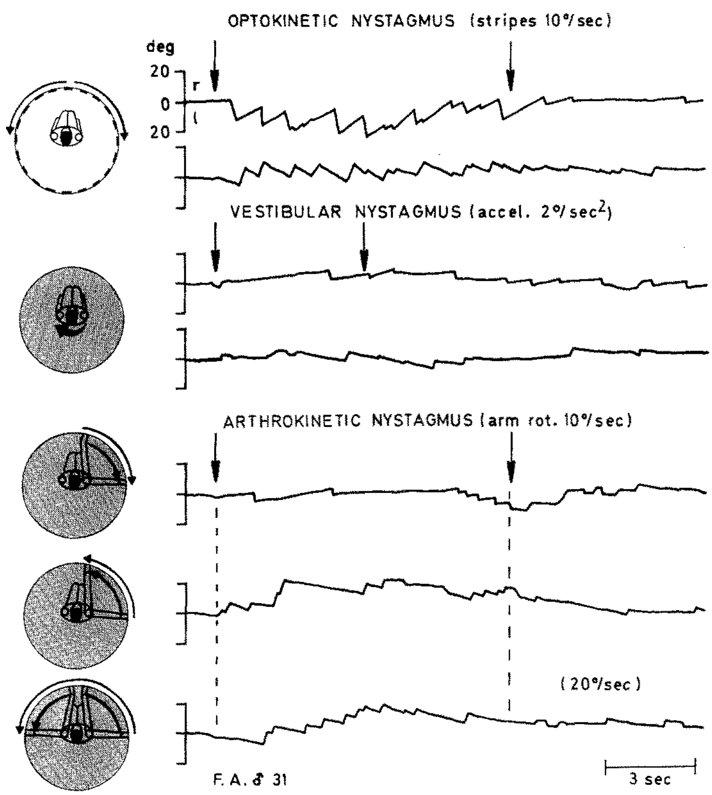

Fig. 2. Comparison of nystagmus induced by optokinetic, vestibular and somatosensory stimulation in two subjects. Stimulus conditions are schematically depicted on the left; for further explanations see methods

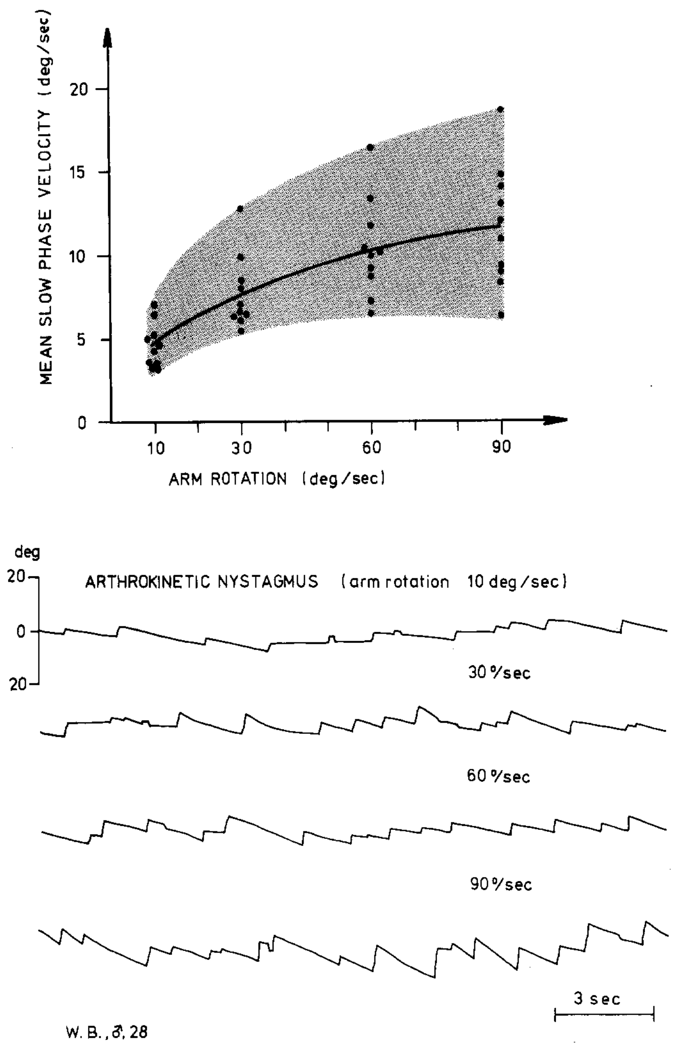

Fig. 3. Mean slow phase velocities of arthrokinetic nystagmus (10 subjects) as a function of arm speed (upper part); one original recording of horizontal arthrokinetic nystagmus (lower part)

c) *Arthrokinetic nystagmus and arthrokinetic circularvection* (CV) were induced by a passive rotation of the arm at the shoulder joint about an earth vertical axis. The angle of rotation for one arm subtended 100°; the speed was determined by a constant velocity drum rotation of either 10°/sec (one arm experiment) or 20°/sec (two arms experiment). Subjects sat with their head fixed in complete darkness and extended the arm in the horizontal plane. Upon command, they made hand contact with the slowly moving wall of the drum. The starting position of the right or left arm was either directly to the side or to the frontal position so that the movement, depending on the direction of drum rotation, was to the left or to the right (Fig. 1).

To increase stimulus velocity without a corresponding shortening of stimulus duration a combination of arm movements was undertaken: The movement of the right arm from the side to the frontal position was immediately followed by that of the left arm from the frontal to its side position (Fig. 2).

In a subsequent experiment ten subjects were exposed to repeated arm rotations as described before but with increasing angular velocity of 10, 30, 60 and 90°/sec. This was undertaken to measure the relationship between stimulus speed and slow phase velocity of induced nystagmus. Mean slow phase velocities were calculated for periods of 10 sec (Fig. 3).

Finally, eye movements were also recorded in a control experiment in which the subject made comparable arm movements; the arm being voluntarily rotated without drum contact through an angle of 100°.

Results

Arthrokinetic Nystagmus

Passive rotation of the arm in all ten subjects induced a more or less pronounced nystagmus with the fast phase beating opposite in direction to arm movement (Fig. 1). It occurred with a latency of between one and several seconds after stimulus onset and usually outlasted the end of stimulation for another several seconds (arthrokinetic after-nystagmus). The *slow phase velocity* of the nystagmus was lower than the speed of the drum (10°/sec and 20°/sec) reaching about 50% of the actual arm velocity. However, when compared with the vestibular nystagmus evoked by the $2°/sec^2$ acceleration to 10°/sec, arthrokinetic nystagmus was mostly stronger for the same subjects, but weaker than optokinetic nystagmus with the stripes moving at 10°/sec (Fig. 2). It was striking that the nystagmus induced by joint movement was associated with a deviation of the mean eye position ("Schlagfeld-Verlagerung") of about 10–30° in the direction of apparent self-motion. The experiments with repeated arm rotations at different speeds showed that the slow phase velocity increases with increasing stimulus speed (10–90°/sec) but does not exceed 15°/sec as a mean.

The intensity of arthrokinetic nystagmus revealed great intra- and interindividual differences; it seemed to be dependent upon vigilance. Eye movements were most pronounced in the two arms experiments at the higher stimulus velocities. Nystagmus was also provoked when the eyes were closed. In one subject who showed a physiological spontaneous nystagmus to the right, this was enhanced if the arthrokinetic nystagmus was also to the right but inhibited if it was directed to the left.

Active arm movements, however, and extension of both arms sideways in such a manner that the drum slipped under the flats of the hands, did not elicit nystagmus, or modify the eye movements in the subject with spontaneous nystagmus.

Arthrokinetic Circularvection

In all ten subjects passive rotation of the arm induced within one to three seconds a compelling illusion of self-rotation in the opposite direction to that of the arm movement. This illusion was indistinguishable from true body motion and like the induced nystagmus showed a considerable after-effect. The angular velocity of arthrokinetic CV frequently was estimated as being greater than the stimulus velocity of 10°/sec. When the shoulder joint was out of the axis of drum rotation a combination of both linearvection and circularvection was perceived. On one occasion in one subject a pronounced rotational vertigo, accompanied by a regular nystagmus which lasted for minutes, was elicited by one arm movement.

The sensation of self-motion with a corresponding nystagmus could also be induced by passive rotation of one leg in the hip joint.

Discussion

Nystagmus, an alternating sequence of quick phases (saccades) and slow phases (eye tracking) can be induced by vestibular or optokinetic stimulation. It is also evoked by other stimuli such as: torsion of the cervical vertebral column (Bos and Philipszoon, 1963), a moving sound source (von Stein, 1910; Dodge, 1923; Hennebert, 1960; Ganz et al., 1969), imagination of a moving visual image (Zikmund, 1966) or by hypnotic suggestion of seen motion (Brady and Levitt, 1964). The regular sequence of alternating quick and slow motor activity is not restricted to the eyes. It is also observed in the neck muscles in man and as a movement of the ears of rabbits (Schaefer, 1972) in response to visual or vestibular stimuli.

This paper deals with the finding of a somatosensory or arthrokinetically induced nystagmus and perception of self-rotation. Arthrokinetic circularvection and nystagmus show some similarities with optokinetic nystagmus and optokinetic circularvection (Mach, 1875; Fischer and Kornmüller, 1930; Dichgans and Brandt, 1977). In contrast to vestibular information, visual and somatosensory motion stimuli can be interpreted as either object motion or self-motion. Whether self-motion is perceived through vision depends on critical stimulus characteristics such as the number of moving contrasts, total area of the stimulus field, stimulation of the seen periphery, foreground-background relations etc. (Brand et al., 1973, 1975; Held et al., 1975; Berthoz et al., 1975). The sensation of an audiokinetic circularvection through movement of acoustic sources (Urbantschitsch, 1897; von Stein, 1910; Dodge, 1923) mostly is less compelling. Both optokinetic and arthrokinetic nystagmus exhibit a deviation of the mean eye position (Schlagfeld) in the direction of the fast phase and, therefore, into the direction of perceived self-motion. At the end of stimulation, arthrokinetic CV and nystagmus show a considerable positive after-effect as is found with optokinetic-stimulation (Brandt et al., 1974). Microelectrode studies in animals have indicated that optokinetic CV is based on a visual-vestibular convergence within the vestibular nuclei (Dichgans and Brandt, 1972; Dichgans et al., 1973; Henn et al., 1974; Allum et al., 1976; Daunton and Thomson, 1976). Optokinetic after-effects probably also involve the central vestibular system in the brain stem and archi-cerebellum (Cohen et al., 1973; Uemura and Cohen, 1973; Brandt et al., 1974; Dichgans and Brandt, 1977).

The question is, which elements of the nervous system subserve the somatosensory type of self-motion perception and nystagmus. From the experimental data extensively reviewed by Kornhuber (1972) and Skoglund (1973) it may be concluded that the muscle receptors do not significantly contribute to kinaesthesis. However, it has long been recognized (Goldscheider, 1889) that the joint receptors enable man to detect changes of limb position as small as one angular degree. Three types of joint receptors have been found in most joints (Gardner, 1950; Skoglund, 1973) which signal the exact position of the joint as well as the direction and speed of movement: Ruffini-like receptors in the capsule, called Golgi-tendon-organs when situated in the ligaments, secondly encapsulated Pacinian corpuscles and thirdly free nerve endings. The absence of an arthrokinetic CV and nystagmus with active arm movements may be due to a collateral efferent inhibition of somatosensory afferents, as first postulated by von Holst and Mittelstaedt (1950). The nervous pathways of the joint afferents via the dorsal funiculi and the lateral spinocervical tract finally project to the anterior lobe of the cerebellum and to somatosensory cortical areas I and II by way of the ventrobasal thalamic nuclei (Mountcastle et al., 1963). A somatosensory-vestibular convergence has been found in animal experiments in the ponto-mesencephalic brain stem (Potthoff et al., 1967) and the vestibular nuclei (Fredrickson et al., 1966).

The existence of arthrokinetic CV and nystagmus strongly indicates a functionally significant somatosensory-vestibular convergence within the central vestibular system (vestibular nuclei and thalamus) at least for afferences carrying positional and kinaesthetic information from the joints. This convergence finally leads to an activation of the neuronal circuits of the paramedian pontine tegmentum, producing nystagmus and mediating the sensation of body movement. It can be assumed that somatosensory joint afferences play a powerful role within the multisensory processes of self-motion perception. Optimal functioning requires the continuous evaluation of the reafferent sensory consequences of self generated body movements and a mutually interactive calibration of the three main loops, visual, vestibular and somatosensory.

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