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VESTIBULAR RESPONSES AND MOTION SICKNESS DURING PITCH, ROLL, AND YAW SINUSOIDAL WHOLE-BODY OSCILLATION

F.E. Guedry, J.W. Norman, G.T. Turnipseed, and A.H. Rupert

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Naval Aerospace Medical Research Laboratory

Naval Air Station

Pensacola, Florida 32508-5700

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J. A. Brady
A. BRADY, CAPT, MSC USN
Commanding Officer



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SUMMARY PAGE

THE PROBLEM

This study evaluates vestibulo-ocular reflex responses to pitch, roll, and yaw whole-body motions and associated incidences of sickness. From the pitch, roll, and yaw responses, we derive time constants that are fundamental to models for predicting responses to forces sensed by the body during change in orientation of the head and body relative to the earth. This work is supported by an Office of Naval Research Accelerated Research Initiative on Vestibular Transduction, which has as one of its main objectives development of basic information on spatial orientation and motion sickness.

FINDINGS

Significant differences were found for the long time constant of the vestibulo-ocular reflex (VOR) between pitch- and roll-axis stimuli. The time constant is short for the pitch axis, intermediate for the roll axis, and long for the yaw axis. Motion sickness appeared to be related to the amount of vertical semicircular canal stimulation received with no clear difference between roll-axis and pitch-axis groups.

RECOMMENDATIONS

Our observations indicate that yaw, pitch, and roll vestibulo-ocular reflex time constants differ significantly from one another under the conditions of this experiment. These time constants are parameters in models for predicting reactions in complex acceleration environments. Further studies are needed to investigate constancy of these time constants during VOR suppression/augmentation by otolith, visual, or spino-vestibular interaction.

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INTRODUCTION

Fundamental differences in several aspects of responses elicited by vertical and horizontal canal stimulation have been reported (1-7). These include differences in the fundamental dynamic characteristics of the vestibulo-ocular reflex (VOR) and differences in provocation of motion sickness, possibly reflecting a common underlying mechanism. In this paper, we examine the phase shift between stimulus velocity and eye velocity during sinusoidal variation in stimulus velocity. By varying head position relative to the axis of rotation, we compare the phase shift and the derived long time-constant for the vestibulo-ocular reflex during pitch, roll, and yaw stimulation. We also compare indices of motion sickness in relation to the preponderance of activation of lateral, anterior, and posterior semicircular canals in our different stimulation modes.

METHODS

SUBJECTS

Subjects were 75 male, preflight naval aviation students from 21 to 26 years old. They were divided into 5 groups of 15. Each group was assigned to one of five experimental conditions.

APPARATUS

The principal equipment item was the Human Disorientation Device (HDD). This device is capable of rotating human subjects with heads on rotation center about either of two independently controlled orthogonal axes (8), one vertical, the other horizontal.

The vertical axis is aligned with gravity and carries a yoke that contains the bearings for the horizontal axis. A large lightproof aluminum capsule houses the subject's chair. In this experiment, vestibular stimuli were always delivered by rotation about the vertical axis, but subjects were placed in different head and body positions relative to the vertical axis.

PROCEDURES

Condition I (Group I)

Subjects were positioned so that the interaural head axis (y-axis) was aligned with the HDD vertical rotation axis. Within the capsule, the subject's chair was positioned so that the subject faced the pivot point of the horizontal rotation axis of the HDD. By rolling the capsule 90 deg about the HDD horizontal axis, the originally upright subject was placed in rightside-down lateral position. With this configuration, rotation of the HDD about its vertical axis delivered a pitch stimulus (y-axis) to the vertical semicircular canal and minimal stimulation to the horizontal canals. The distance from the center of rotation to the subject's feet was about 96 cm.

Condition II (Group II)

Subjects were in a normal upright seated position with the head ventroflexed 20 deg so that a line from the outer canthus to the tragus was earth-horizontal. During rotation of the HDD, this head and body

configuration maximized stimulation of the horizontal semicircular canals (z-axis) and minimized vertical semicircular canal stimulation.

Condition III (Group III)

Subjects were seated in normal upright posture, but they turned their heads (in yaw) 90 deg left and leaned forward to position the head with right ear down on a horizontal pad. With the chair offset slightly from rotation center, the interaural axis was aligned with the rotation axis, and the body envelope was maintained near the center of rotation. In this head and body configuration, stimulation of the vertical semicircular canals in pitch (y-axis) was maximized as in Group I, but unlike Group I, G-gradients on the lower body were minimized.

Condition IV (Group IV)

Subjects were seated with head erect (not ventro-flexed) in normal upright posture. The subject's chair faced at a right angle to the horizontal axis of the HDD. The capsule was then rotated 30 deg backward about the HDD horizontal axis to place the subject in a semi-faceup position. With the subject thus positioned, the horizontal canals were about 50 deg from the plane of rotation. This configuration yielded roll (x-axis) stimulation to the vertical semicircular canals and approximately equivalent stimulation to the horizontal canals (9).

Condition V (Group V)

Conditions were identical to Condition IV except that the HDD capsule was rotated backward 60 deg to place subjects in nearly faceup position for rotation about the HDD vertical axis. This configuration generated strong roll (x-axis) stimulation of the vertical semicircular canals and weak stimulation of the horizontal canals. The horizontal canals were about 80 deg from the HDD plane of rotation.

For all groups, the vestibular stimulus was sinusoidal variation in angular velocity about an earth-vertical axis at a frequency of 0.04 Hz and peak velocity of ± 120 deg/s. Subjects were exposed to five, 4-min intervals of stimulation separated by 3-min rest intervals. Overall, the motion exposure session lasted for slightly more than 30 min except for subjects who were unable to complete the session due to motion sickness. During motion exposure, the capsule was in complete darkness except for 1.0 min at the end of the first 4-min interval during which the capsule interior was illuminated.

Eye movements were measured by electrooculography (EOG) with electrodes placed at the outer canthus of each eye, above and below the right eye, and a reference electrode high on the forehead. Time constant of amplification of EOG was 3.0 s. Because of the position of subjects' heads relative to the axis of rotation, vertical nystagmus comprised the VOR response in Groups I and III. To achieve measurement of the VOR in Groups IV and V, subjects were instructed to gaze downward, 30 deg in Group IV, and 60 deg in Group V. With gaze so directed in Groups IV and V, the VOR can be recorded by horizontal electrodes according to Fetter et al. (10). To assist subjects of Groups IV and V in gaze direction, a small red target light appropriately positioned was presented for 10 s just before each 4-min interval of stimulation. Twice

during each 4-min interval, the target light was flashed on for approximately 1 s to provide a gaze-direction reminder.

Three sickness assessment ratings were used to evaluate motion sickness:

Self-rating 1 (SR-1). Subjects rated themselves before and after each 4-min stimulation interval. A magnitude scale of 1-7 was used with 1 signifying no feeling of motion sickness and 7 signifying severe nausea with vomiting imminent.

Self-rating 2 (SR-2). Subjects filled out a self-rating form used in several previous studies to evaluate the effects of provocative stimulation. This self rate was obtained immediately after subjects exited the HDD after completing (or aborting) their last stimulation interval.

Observer Rating (OR). Immediately after the last stimulation interval was completed, the observer rated subjects with a form used in previous studies (11,12). The SR-2 and OR scores provide comparison to levels of sickness encountered in past studies with other motion stimuli (11).

Before the experiment, subjects were told that the rotation stimulus might produce sickness in some individuals. They were asked to forewarn the experimenter if vomiting was imminent. Subjects were permitted to withdraw from the experiment without prejudice in accordance with standard informed consent policy.

RESULTS

MOTION SICKNESS

Signs and symptoms of motion sickness were virtually negligible in Group II, slight in Group IV, and clearly present in Groups I, III, and V. Table 1 reflects mean data from each of the five groups by three rating systems used to evaluate sickness

TABLE 1. Mean Sickness Ratings, Percentage Aborts, and Percentage Symptom Free.

Rating	Group				
	I	II	III	IV	V
SR-1	13.13	5.87	19.13	7.67	15.80
SR-2	12.27	7.07	14.33	7.87	13.93
OR	12.13	7.27	18.27	9.07	14.27
% aborts	20	0	47	7	27
% symptom free	25	47	13	47	20
N	15	15	15	15	15

By both parametric and nonparametric statistical treatments, between-group differences in means were statistically significant ($p < .01$). Group IV sickness measures were slightly higher than those of Group II, but the difference was not statistically significant. Groups I, III, and V sickness measures were all significantly higher ($p < .01$) than those of Group II.

Similarly, Groups I, III, and V sickness measures were higher than those of Group IV with Groups III and V clearly achieving statistical significance, while the Group IV-I mean difference achieved significance on two of the three measures.

Groups I and V were very similar; slight mean differences in motion sickness measures were not statistically significant. Groups I and III appear to differ, but ordinary statistics only approached significant probability levels.

Following 20 min of motion exposure, Groups I, III, and V had SR-2 and OR scores about equal to those (14.0 and 13.9) in an earlier study (11,12). Mean abort rate over Groups I, III, V within our first 4-min stimulation interval was 6.7%, slightly greater than the 3.1% observed in the earlier study. The nauseogenic properties of our pitch and our roll sinusoidal stimuli were comparable to a 5-min period of Coriolis cross-coupled stimulation comprising 10 head movements (45 deg pitch or roll) made during 90 deg/s whole-body rotation.

STIMULUS RESPONSE PHASE RELATIONS

The slow phase velocity of the VOR approximately compensates (gain 0.6) for the angular velocity of the head during 0.04-Hz sinusoidal passive vestibular stimulation. As the stimulus angular velocity decreases, stops, and reverses direction, the VOR slow phase velocity does likewise with a phase advance; the point of reversal of VOR slow-phase velocity slightly precedes the point of reversal of the stimulus during steady-state oscillation. The quality and consistency of vestibular-nystagmus tends to be improved by tasks that increase and regularize mental arousal (13). For this reason, subjects performed mental arithmetic for 50 s (2 cycles) during each of the five stimulation intervals. The VOR recording during mental arithmetic was examined to measure stimulus response phase angles.

The recording method for the x-axis VOR was that used by Fetter et al. (10), specifically electrooculography. With subject's z-axis tilted backward 30 deg (Group IV) or 60 deg (Group V) and the subject's gaze directed along his x-axis, rotation about an earth-vertical axis with the head centered would produce predominately a roll-axis VOR particularly with Group V. A VOR roll-axis response would not be adequately detectable by EOG. However, with the gaze directed downward 60 deg below the x-axis, as in Group V, the VOR appears to occur about a functionally appropriate axis, namely one that would reduce "retinal slip" for earth-fixed targets in the plane of the direction of gaze. Thus, electrodes at the outer canthus of each eye, "horizontal electrodes," provided a good recording of nystagmus and measures of the "zero crossing" (point of reversal) of the VOR during sinusoidal roll-axis stimulation.

Phase data are shown in Table 2. Between-group mean differences in phase were highly significant ($F_{3, 49} = 30.6$, $p < .001$). Due to equipment failure, Group II VOR data from the present study are not available, but from past work, the expected temporal phase advance in Group II is on the order of 1.0 s.

TABLE 2. Mean Phase Advance Measured in Seconds of VOR Slow-phase Velocity*.

Rating	Group				
	I	II	III	IV	V
Mean phase	2.54	(1.2)	2.11	1.26	1.49
SD	0.475	(.35)	0.347	0.309	0.425
N	15	(109)	12	14	12

*Substituted Group II VOR phase estimates from earlier studies (14).

More detailed analysis (Table 3) indicates that both pitch-axis groups (I & III) differed significantly from both roll-axis groups (IV & V) but did not differ significantly from one or another. The two roll-axis groups did not differ significantly from one another.

TABLE 3. Between-group F-value Comparisons.

Group	Group			
	I	III	IV	V
I	-	6.9	75.6	47.1
III		-	31.8	17.5
IV			-	2.1

Scheffe post-hoc critical values: .05 = 8.33, .01 = 12.6.

Converting the temporal phase angle from seconds to degrees of the .04-Hz stimulus cycle, the stimulus-response phase angles were 36.6, 30.4, 18.1, and 21.4 deg for Groups I, III, IV, and V, respectively. For Group II, the phase angle estimate is 17.6 deg.

DISCUSSION

Stimulus axes were selected in the present experiment to vary the amount of vertical semicircular canal stimulation received by different groups. The axis of the stimulus is localized in three dimensions relative to the head by distinctive patterns of primary afferent activity from the six semicircular canals. Each distinctive pattern constitutes a code by which the central nervous system sets off reflexive eye movements in a plane appropriate to the axis of the stimulus. The magnitude of the stimulus to each canal is encoded by the magnitude of the change from resting level of afferent activity from the primary afferents of the canal. The magnitude of the stimulus to a given canal is dependent on the angle between the mean plane of the canal and the plane of the stimulus and can be estimated from

$$\alpha_c = \alpha \cos \phi \quad (1)$$

where α_c is the component of the stimulus acting in the plane of the canal, α is the magnitude of the angular acceleration stimulus, and ϕ is the angle between the mean plane of the canal and the plane of the stimulus.

Presumably, rotation of the head about any head axis stimulates all six semicircular canals. Table 4 presents estimates of the relative magnitudes of horizontal, anterior, and posterior canal stimulation received by the five groups based on anatomical geometric data of Curthoys et al. (9). From Table 4, we believe that Groups I and III received a preponderance of vertical canal stimulation, especially anterior canals. Group II received a strong preponderance of horizontal canal stimulation. Group IV received equivalent horizontal canal and posterior canal stimulation while Group V received preponderant vertical canal stimulation, especially posterior canal.

TABLE 4. Relative Magnitudes of Vertical and Horizontal Semicircular Canal Stimulation Received by Each Group.

Canal	Group				
	I	II	III	IV	V
Horizontal	.16	.90	.16	.64	.18
Anterior	.75	.02	.75	.28	.55
Posterior	.56	.32	.56	.65	.81

VOR TIME CONSTANTS

The cupula-endolymph system in each semicircular canal has been likened to a heavily damped torsion pendulum (15). The response of such a system to various angular acceleration profiles can be predicted when values are known for three parameters: the inertia, the friction, and the spring action terms in the differential equation appropriate for this kind of system. The "long time constant," T_c , is the ratio of two of these parameters, the friction term (degrees/second) divided by the spring action term (degrees). Solving the differential equation for the predicted decay of response, R , following an initial cupula deflection, D , provides a working equation for estimating T_c :

$$R = KD_e^{-(t/T_c)} \quad (2)$$

In equation 2, when t (time elapsed following cupula deflection) equals T_c , R will have decayed to $KDe^{-1} = 0.37 KD$ where K is a constant of proportionality between cupula deflection and the particular response (e.g., the VOR) being measured. Thus, T_c can be estimated by measuring the time from termination of a stimulus that deflects the cupula until the response decays to 37% of its initial magnitude. Fetter et al. (10) reported the T_c of roll-axis VOR responses (calculated from the measured decay rate of the VOR response to an angular impulse) are shorter than would be expected from responses to yaw-axis stimulation.

Estimates of T_c can be calculated from our data by measuring the stimulus-response phase angle that occurs with sinusoidal stimuli. Solution of the differential equation for the sinusoidal stimulus conditions of this experiment provides a predictive equation for stimulus-response phase angle,

$$\phi = 90^\circ - \tan^{-1}(\omega T_c) \quad (3)$$

where ϕ is expressed in degrees, and ω is the stimulus frequency expressed in radians per second. When measures of ϕ are available as they are in our data, T_c , expressed in seconds, can be estimated by:

$$T_c = \frac{1}{\omega} \tan(90^\circ - \phi) \quad (4)$$

By converting our temporal measures of the VOR slow phase velocity phase advance (relative to the stimulus velocity) into degrees of the stimulus cycle we obtained measures of ϕ for the different groups.

Substituting our mean values of ϕ into equation 4, we obtain 5.4, 6.8, 12.1, and 10.1 s as estimates of T_c for Groups I, III, IV, and V respectively. From previous findings (14), we estimate the T_c for Group II to be on the order of 12.5 s. The long time constant of the VOR appears related to relative magnitude of horizontal canal component elicited by the stimulus (see Table 4).

If T_c values for vertical canal responses are shorter than T_c values for horizontal canal responses, then the mean T_c value for Group V should have been less than that for Group IV and about equal to those for Groups I and III. The ordinal relationship of the calculated T_c values for the different groups was actually consistent with this expectation, but all expectations were not met. The mean difference in T_c values for Groups IV and V was in the predicted direction, but it did not achieve statistical reliability. On the other hand, mean differences between Groups V and I and between Groups V and III were statistically significant and fairly large. The mean T_c value for Group V is consistent with the mean value (11.25) calculated elsewhere (10) from responses of five subjects to ramp function stimuli.

These differences in time constants are probably not attributable to differences in the dynamics of cupula-endolymph movement in the different sets of canals. Time constants measured at the level of the primary afferents of the horizontal canal are on the order of 3-5 s (16), which is much shorter than those estimated from horizontal nystagmus. A central "velocity storage" network has been proposed (17,18) to account for differences in response dynamics at peripheral and more central levels of the nervous system. Presumably, the central network is differentially effective in lengthening the time constants of higher level responses set off by the horizontal and vertical canals. Why would this be? We propose that vertical canal responses are functionally tied to inputs from the otolith and neck proprioceptor systems, which serve to shape their dynamics. Why would we have a pitch and roll difference? This difference may be tied to natural head-neck articulation. Roll head-neck movements are difficult to generate and are infrequent relative to pitch head-neck movements. All pitch head movements made from natural upright posture involve simultaneous inputs from the vertical canals and the otolith system. Many yaw head movements do not involve this tight coupling of canal-otolith input as when the z-axis nears alignment with gravity, but some yaw head movements do as when the z-axis is substantially misaligned with gravity. Thus, otolith-canal coupling is strong for pitch, less for roll, and variable for yaw. What evidence do we have that time constant can be shaped by interactions between systems? The time constant of horizontal nystagmus is altered by repetitive stimulation, particularly in the presence of visual stimulation that suppresses the vestibular reaction (14). Similarly, canal-dependent vestibular nystagmus is altered by changes in otolith stimulation

(19-21). We infer that otolith-canal interactions that routinely accompany vertical canal stimulation shape time constants of reactions set off by the vertical canals.

MOTION SICKNESS

The mean sickness measures for the different groups appear related to the amount of vertical canal stimulation experienced by the groups. Group II had minimal vertical canal stimulation and experienced no sickness. Group IV received moderate vertical canal stimulation and experienced a low incidence of sickness. Groups I, III, and V received predominantly vertical canal stimulation, and these groups clearly exhibited signs and symptoms of motion sickness.

Groups I and III presumably had identical vertical canal stimulation about the "pitch" axis. One hypothesis from previous incidental observations (1) attributed sickness to phase angle mismatches between G-gradient cues from the lower body and cues from the semicircular canals, particularly the vertical semicircular canals. While the results of the present experiment do not refute this hypothesis with certainty, they call it into question. The head and body configuration of Group III subjects reduced G-gradient cues on the lower limbs relative to cues experienced by Group I (and by Groups IV and V); yet sickness measures were greater in Group III than in Group I. Assuming that the mean difference between Groups I and III is reliable, the obvious possibility is that the abnormal head and body configuration of Group III exacerbated the nauseogenic properties of the vestibular stimulus, possibly by introducing non-physiologic vestibulo-spinal reflexes that could alter normal coordination (22-25) of various sensorimotor inputs more than any effects from G-gradients on the lower body.

Several observations (3,5,6) have suggested that pitch axis vestibular stimulation is more provocative than roll axis stimulation. The similarity of sickness results for Groups I (pitch) and V (roll) does not support this notion, at least for conditions of this study.

In describing our VOR data, we have referred to the slow phase velocity of the eyes relative to the angular velocity of the stimulus. Specification of the velocity of the stimulus (as opposed to angular acceleration, which is the adequate stimulus) has been widely used in vestibular research, particularly with sinusoidal stimuli for the following reasons. From relatively high stimulus frequencies (0.5-5.0 Hz) often encountered in natural movement (26,27) to unnaturally low frequencies like the stimuli used in this study, slow-phase eye velocity very nearly compensates for the angular velocity of the head. During head and body movement, the reflex serves to stabilize angular position of the eye relative to the earth. Perceived whole-body rotation is also very nearly "on" the velocity of the stimulus waveform. Like VOR, the perceptual reaction is phase-shifted relative to the stimulus throughout the cycle, but perceived velocity is zero when the stimulus velocity nears zero, which is the point at which the angular acceleration approaches maximum. In other words, reactions are least where the stimulus acceleration approaches maximum and near maximum where the acceleration is zero. Such is the dynamic response of this system to sinusoidal stimuli, and the response is said to be "on velocity" and not "on acceleration."

With the pitch-axis stimulus (Groups I and III) in this study, the VOR and the perceived stop or point-of-reversal preceded the actual point-of-reversal by more than 2 s. Though the stimulus-response phase shift was present throughout the cycle, the phase shift seemed to be most appreciated near zero velocity. The subject experiences a mismatch between vestibular angular velocity information and various extraneous cues (auditory, vibratory, and tangential acceleration cues). An experience sometimes called paradoxical motion in which different directions of motion are simultaneously perceived. Because the phase advance was greater for the pitch stimulus (Groups I and III) than for the yaw stimulus (Group II), a higher sickness incidence in Groups I and III than in Group II would be expected on the basis of the sensory mismatch theory of motion sickness (28,29). Our results are consistent with this expectation, but the results of Group V do not quite fit the picture. The mean stimulus-response phase angle in the roll (x-axis) motion experienced by Group V was significantly shorter than that of Group I (y-axis), yet, in Groups V and I, sickness incidence was quite similar.

Most theoretical speculations about stimuli that induce motion sickness can be divided into two categories. The first one attributes motion sickness to an excessive magnitude of vestibular stimulation, and often a vestibular receptor is indicted, for example, "canal-sickness" or "otolith-sickness." The second one attributes motion sickness to unusual motion stimuli that induce sensory mismatches concerning the state of motion of the head and body. The common thread in our results is the putative relationship between the distribution of vertical and horizontal canal stimulation and sickness incidence, but we do not suggest a "vertical-canal-sickness" interpretation. The magnitude of the peak angular accelerations in our stimulus waveform, 30 deg/s^2 , is far less than the magnitude of angular accelerations involved in natural everyday head movements, and the peak angular velocity is roughly the same as peak velocity of natural head oscillations of 1 or 2 Hz.

Our stimulus-response condition differs from oft-experienced conditions in several ways: stimulus frequency, passive stimulation, total integrated unidirectional reaction in each half of the stimulation cycle, and the aforementioned large stimulus-response phase angle. Another unusual aspect of our stimulus, particularly for the vertical canals, is the concomitant stimulation of the otolith system. As discussed above, pitch-head movements made from natural upright posture always set off coordinated inputs from the canalicular and otolithic vestibular structures. Our stimulus violated this natural intra-vestibular concordance. Substantial vertical canal stimulation occurred in the absence of concordant change in position inputs from the otolith system. The significance of this concordance or lack of it to vestibular responses is well supported. Asymmetry in upward-downward VOR (9) may not be present when stimulus conditions produce intra-vestibular concordance (30). Adaptive change in VOR to one set of motion cues is disrupted when position relative to gravity is changed (31). The rate of decay of the VOR in response to an angular impulse is altered by a change in head orientation relative to gravity (19,20,32).

In considering the several divergent properties of our stimulus relative to commonly experienced natural stimuli, we do not propose that one property should be selected for emphasis. Rather, we suggest that all of the ways in which our stimulus differs from common experience would require sensorimotor adaptive change for functional adaptation to such stimulus conditions. The requirement for adaptive change to stimuli involving the vestibular system

seems to be associated with an increasing probability of motion sickness. Otherwise expressed, motion sickness is a by-product of the onset of adaptation to conflicting sensory information on the state of motion of the body (28,29), perhaps for reasons suggested by Money (33). Our vertical canal stimuli introduced conflict. We suggest that both the greater phase advance and the intra-vestibular conflict served to provoke motion sickness with our vertical canal stimuli.

RECOMMENDATIONS

Our observations indicate that yaw, pitch, and roll vestibulo-ocular reflex time constants differ significantly from one another under the conditions of this experiment. These time constants are parameters in models for predicting reactions in complex acceleration environments. Further studies are needed to investigate constancy of these time constants during VOR suppression/augmentation by otolith, visual, or spino-vestibular interaction.

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Other Related NAMRL Publications

None are applicable.