INFLUENCE OF LABYRINTH ORIENTATION RELATIVE TO GRAVITY ON RESPONSES ELICITED BY STIMULATION OF THE HORIZONTAL SEMICIRCULAR CANALS

Manning J. Correia and Fred E. Guedry, Jr.

JOINT REPORT

UNITED STATES NAVAL SCHOOL OF AVIATION MEDICINE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Research Report

INFLUENCE OF LABYRINTH ORIENTATION RELATIVE TO GRAVITY

ON RESPONSES ELICITED BY STIMULATION OF THE HORIZONTAL

SEMICIRCULAR CANALS*

Manning J. Correia and Fred E. Guedry, Jr.

Bureau of Medicine and Surgery
Project MR005.13-6001
Subtask 1 Report No. 100

NASA Order No. R-93

Approved by

Captain Ashton Graybiel, MC, USN
Director of Research

Released by

Captain H. C. Hunley, MC, USN
Commanding Officer

2 September 1964

* This research was conducted under the sponsorship of the Office of Life Science Programs, National Aeronautics and Space Administration.

U. S. NAVAL SCHOOL OF AVIATION MEDICINE

U. S. NAVAL AVIATION MEDICAL CENTER

PENSACOLA, FLORIDA

SUMMARY PAGE

THE PROBLEM

Examination of the effects of different orientations of the horizontal semicircular canal cupulae relative to gravity on nystagmic output following deceleration from rotation about the horizontal axis.

FINDINGS

Significant differences in responses between some stopping positions were obtained, but results were not completely consistent with those to be expected from a gravity-influenced cupula response. The results appear at least equally indicative of a facilitation, during rotation, and a suppression, after rotation, of canalicular input by gravity sensitive receptors, possibly the otoliths.

Of direct practical significance is the apparent control of motion sickness during this form of stimulation by the mental task assigned to the subject.

ACKNOWLEDGMENTS

The authors wish to express appreciation to the cadets from the U. S. Naval School Pre-Flight, who served as subjects in these experiments, and to AN Albert, Miss Mathis, and Mr. Turnipseed for the execution of these experiments.

INTRODUCTION

A considerable body of experimental evidence has accrued concerning the effects of angular acceleration on the vestibular apparatus when an individual is rotated about the earth-vertical axis. Much of this evidence relates to theoretical speculations in which the mechanics of the semicircular canals (10, 11) have been likened to the action of a heavily damped torsion pendulum. Some insight as to the response characteristics of the semicircular canal cupulae may be gained by examining their response to decelerations from horizontal-axis rotation. Several investigators (1,5) have reported work which involved rotation of subjects about the earth-horizontal axis.

In the case of deceleration following rotation about the vertical axis, the force of gravity acts uniformly downward on the cupulae of the horizontal semicircular canals, is perpendicular to the plane of cupula movement, and probably does not interact with the pendulous response of the end-organ. However, when an individual undergoes deceleration following rotation about the earth-horizontal axis, the horizontal semicircular canals are stimulated as in rotation about the vertical axis, except that the force of gravity acts in the plane of movement of the cupulae of the horizontal canals. If the cupulae are influenced by gravity, the latter circumstance would maximize the interaction between the cupula's spring action and the force of gravity.

As indicated in Figure 1, if there is a cupula-gravity interaction, gravity would oppose cupula return following clockwise rotation with a stop at the 90-degree position, and consequently would increase the return time. Conversely, a stop at 270 degrees following clockwise rotation would decrease return time and yield attenuated responses since cupula return would be aided by the force of gravity. Following counterclockwise rotation (Figure 1) the response relations for 90 and 270-degree stops should be the reverse of those following clockwise rotation.

If the position of the cupula is as indicated in Figure 1, the other two stop positions, 0 degrees and 180 degrees, should yield different duration responses, irrespective of the initial direction of cupula deflection occasioned by the stop. The cupula's return would be impeded by gravity for stops in the 180-degree position and enhanced by gravity for stops in the 0-degree position. Because the direction of cupula deflection would be irrelevant to the outcome in these two situations, no difference should be expected for different directions of rotation. However, it is possible that the long axis of the cupula is not parallel to the sagittal plane and that the cupula "points" medially more than is shown. In this event small differences in response would be anticipated for the 0-degree and 180-degree positions.

The following experiments were conducted to examine the possible influence of gravity on responses initiated by semicircular canal function during and following horizontal-axis rotation.

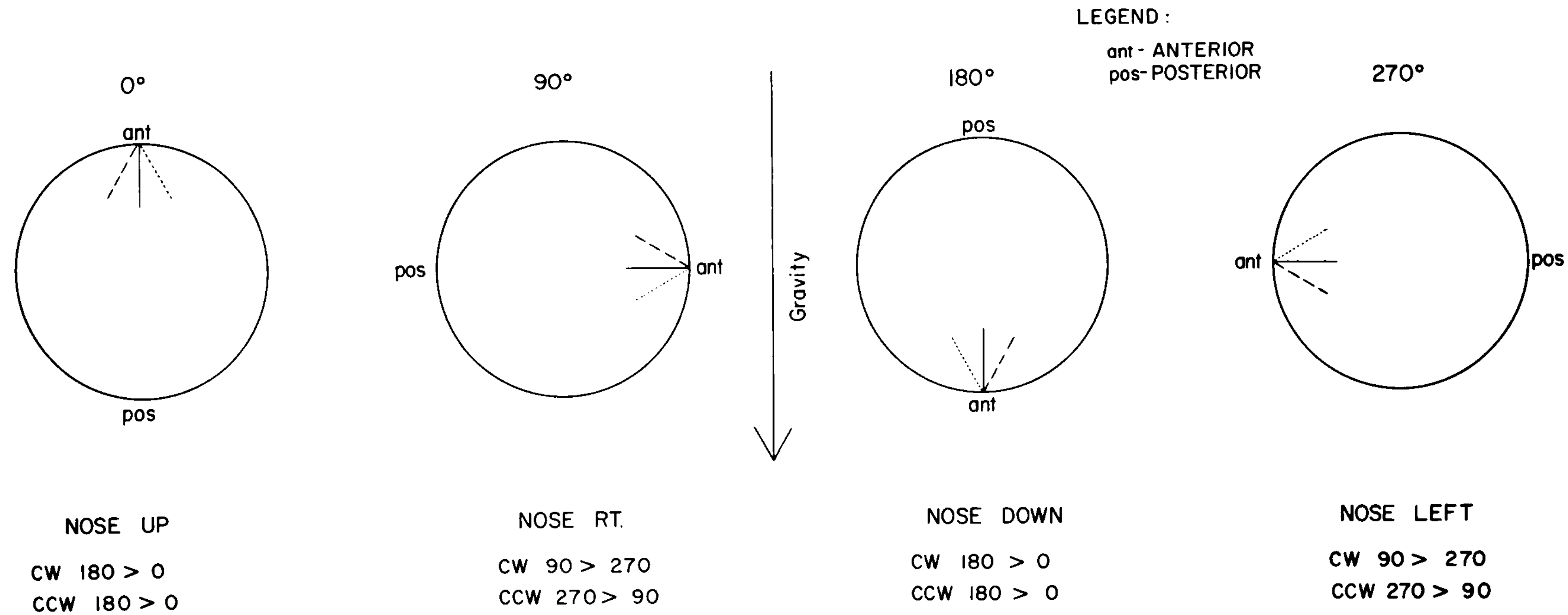

Figure 1

Relation of Deflected Cupula to Gravity with Various Head Orientations (Stop Positions) following Clockwise (....) and Counterclockwise (----) Rotation. The Cupula in Its Resting Position (——) Is Presumed To Be Approximately Parallel to the Sagittal Plane.

PROCEDURE

EXPERIMENT I

Subjects

Sixteen men with normal vestibular function served as subjects. Prior to this experiment none of the subjects had previous exposure to the test apparatus.

Apparatus

The experimental apparatus consisted of a variable position litter (5), a control console for electrically actuating and regulating rotation of the litter, and a Sanborn Model 964 recording system for recording movement of the eyes and of the position litter.

Method

Each subject was given six trials during a testing period, two rotations about the vertical axis and four rotations about the horizontal axis. Half of the subjects were always rotated in a clockwise direction and half in a counterclockwise direction.

On any given trial the subject was accelerated at a constant rate of approximately $20°/sec^2$ to a constant velocity of 60°/sec and maintained at this speed for ninety seconds. The subject was then decelerated at a rate of approximately $20°/sec^2$ to zero velocity. The sequence, magnitude, and duration of accelerations, constant velocities, and decelerations were the same for each of the six trials. The horizontal and vertical trials, however, differed in one respect. Each of the horizontal decelerations was terminated so that the subject's nose was pointing in one of four different directions, nose up (0 degrees), nose right (90 degrees), nose down (180 degrees), or nose left (270 degrees).

The order of presentation of the six trials for a given subject was maintained: one rotation about the vertical axis (pre) followed by four rotations about the horizontal axis and a final rotation about the vertical axis (post); however, the order of stopping positions following horizontal rotation was counterbalanced over subjects.

Twenty-degree eye movement calibrations were obtained for each subject prior to the two vertical rotations and the first of the four horizontal rotations. Subjects were instructed to attend to perceived body movement during the constant velocity period and were questioned about these sensations after each trial.

Horizontal eye movements were recorded for sixty seconds following the onset of deceleration.

Results

The total nystagmic output in degrees for each of the sixteen subjects under each of the experimental conditions is presented in Table I. Each entry represents total slow phase displacement output for a sixty-second interval following onset of deceleration. For each direction of rotation, comparisons were made between responses produced by the initial and final vertical-axis trials (Pre and Post in Table I) and between the 0 versus 180 and 90 versus 270 head-stop positions about the horizontal axis. The t and P values are presented in Table I.

It is evident by inspection (Table I) that responses following rotation about a vertical axis were consistently greater than those following horizontal-axis rotation. Differences in results for various head-stop positions of the horizontal-axis trials are more complicated; further description of these results is reserved for subsequent discussion.

A total of twenty-four subjects were exposed to the experimental procedures. However, eight of the subjects reported such severe cases of nausea and stomach awareness that they did not wish to complete the session; two of the eight actually vomited. Of the sixteen subjects who completed the procedure, eight reported that during the testing session they felt stomach awareness and slight nausea.

EXPERIMENT II

In the preceding experiment several factors were not considered. First, a positional nystagmus, whether the reversing type or the unidirectional type, might appear at the different head-stop positions and consequently facilitate the nystagmic output for one head-stop position and oppose it at another head-stop position. Secondly, the continuing nystagmus during horizontal-axis rotation described previously (5) might interact with the post-rotary nystagmus. And thirdly, the high incidence of sickness evident in Experiment I could suppress nystagmic output during constant velocity (2, p. 102), and consequently interact with post-rotary nystagmus. To consider these factors, several modifications of procedure from the preceding study were employed: 1) Prior to and following the horizontal rotations, each of the sixteen subjects used in this study was positioned at each of the head-stop positions (0, 90, 180, and 270 degrees), and eye movement recordings of forty-five seconds' duration were taken; the angular accelerations involved in achieving each position to test for positional nystagmus were of very low magnitude. 2) During rotation with the axis horizontal, nystagmus during constant velocity was recorded and compared to the positional nystagmus. Additionally, in this experiment the influence of variation in mental states on nystagmus output (4) was examined for constant velocity rotation about the horizontal axis. Eight of the sixteen subjects were asked to press a key at the 0-, 90-, 180-, and 270-degree positions during rotation about the horizontal axis. The other subjects were asked to relax during rotation. Under all cases subjects performed mental arithmetic problems during acceleration and deceleration.

Table I

Total Magnitude Slow Phase Displacement in Degrees of the Nystagmus within a Sixty-Second Interval following Onset of Deceleration

				Horizontal Axis Rotation Stop Position			
Subject	Direction of Rotation	Vertical Axis Rotation Pre	Post	0	180	90	270
Ca	CCW	272	308	126	128	72	105
Ni	CCW	332	426	145	70	100	185
Ch	CCW	202	366	116	106	134	101
Chr	CCW	734	539	252	190	249	236
Wi	CCW	679	721	260	218	238	253
Ru	CCW	322	171	332	211	251	241
Zu	CCW	615	793	408	119	155	429
Ro	CCW	244	377	137	65	139	122
$\bar{x}$		425	463	222	138	167	209
t		.76		2.63		1.17	
P		>.05		<.01		>.05	
He	CW	194	370	91	55	233	100
St	CW	173	296	157	89	116	131
Hor	CW	266	269	176	164	273	120
Va	CW	233	338	139	122	84	92
How	CW	992	1044	216	473	499	166
Kr	CW	205	223	192	143	184	123
Di	CW	571	738	295	307	325	232
Bu	CW	372	354	121	195	168	113
$\bar{x}$		376	454	173	194	235	135
t		2.89		.54		2.59	
P		<.01		>.05		<.01	

Results

A summary of the findings of Experiment II is presented in Table II. Contained in Table II are: 1) the total nystagmic output in degrees for the pre- and post-rotation conditions about the vertical axis and the 0-, 90-, 180-, and 270-degree head-stop conditions about the horizontal axis; 2) the type of response produced by each subject during rotation about the horizontal axis (presented in parentheses following each indicated nystagmic output); 3) the direction of the fast phase of nystagmus as a result of positioning subjects at the 0-, 90-, 180-, and 270-degree head-stop positions about the horizontal axis; and 4) the $\underline{t}$ and $\underline{P}$ values for comparisons between pre- versus post-vertical axis rotation, 0 versus 180, 90 versus 270-degree head-stop conditions following rotation about the horizontal axis.

As in Experiment I, it is evident by inspection (Table II) that the post-rotational responses produced by deceleration from rotation about the horizontal axis were suppressed as compared with vertical-axis post-rotational responses.

DISCUSSION

The results of Experiments I and II presented in Tables I and II failed to provide consistent support for the predictions based on a gravity-cupula interaction following deceleration from rotation about the earth-horizontal axis. The predictions based on a gravity-influenced cupula presented in Figure 1 received reliable support in only two of eight head-stop comparisons in Experiments I and II. In Experiment I, the 90-degree head-stop responses were found to be significantly greater than the 270-degree head-stop responses ($t=2.59$, $P<.01$, d.f.=7) following clockwise rotation, and in Experiment II the 270-degree head-stop responses were found to be greater than the 90-degree head-stop responses ($t=2.15$, $P<.01$, d.f.=7) following counterclockwise rotation. Although mean differences between 90° and 270° stop positions were consistent from Experiment I to Experiment II, the statistical reliability of the differences was not consistent. In regard to the 0- and 180-degree head-stop responses, ambiguity in the results existed. Following counterclockwise rotation in Experiments I and II, the results for 0- versus 180-degree head-stop comparisons were significantly different in a direction opposite to results inferred from an interaction between gravity and cupula spring action, and following clockwise rotation no difference was found. This finding is discrepant with results of McLeod and Correia (9) in which magnitude of nystagmus output in response to caloric stimulation was always found to be significantly greater in the supine position than in the prone position. However, in that study unilateral caloric stimulation was used and the present study involved bilateral stimulation.

An explanation, which is at least as consistent with the results as the possibility of a "cupula-gravity" interaction, derives from the old observation (7, p.300) that looking in the direction of the fast phase potentiates nystagmus. If we assume that following horizontal-axis rotation there is a counterrolling tendency for horizontal eye movement (relative to skull), then in the 90-degree stop position subjects would

Table II

Summary of Results of Experiment II

Subject	Direction of Rotation	Vertical Axis Rotation Pre	Post	Horizontal Axis Rotation Stop Positions 0	180	90	270	Direction of Fast-Phase of Positional Nystagmus Stop Positions 0	90	180	270	Mental Condition during Horizontal Axis Rotation
Bo	CCW	632	460	436(NCR)*	204(NCR)	204(NC)	376(NC)	0	L	0	R	Relaxed
Be	CCW	832	685	201(NC)#	55(NC)	138(NC)	227(NC)	0	0	0	L	Relaxed
Cl	CCW	660	687	210(C) ‡	95(NC)	183(NC)	79(C)	0	0	0	0	Relaxed
Sl	CCW	640	788	201(NC)	236(C)	157(C)	263(C)	0	0	0	0	Relaxed
$\bar{x}$		691	655	262	148	171	236					
St	CCW	789	705	126(NC)	46(NC)	54(NC)	198(NC)	0	0	0	0	Key press
Ho	CCW	274	328	73(C)	116(NC)	72(C)	223(NC)	0	0	0	0	Key press
Fi	CCW	333	416	151(NC)	145(NC)	106(NC)	157(NC)	0	0	0	0	Key press
Mi	CCW	525	607	258(C)	116(C)	221(C)	119(C)	0	0	0	0	Key press
$\bar{x}$		474	514	152	106	113	174					
$\bar{\bar{x}}$		585	585	207	127	142	215					
$t_{\bar{\bar{x}}}$		0		2.35		2.15						
$P_{\bar{\bar{x}}}$		>.05		<.01		<.01						
Wi	CW	738	467	233(NC)	231(NC)	281(NC)	286(NC)	L	L	L	L	Relaxed
Lo	CW	154	414	192(NC)	134(NC)	307(C)	155(NC)	L	L	0	0	Relaxed
Sp	CW	204	243	123(NC)	115(NC)	182(NC)	95(NC)	0	0	0	0	Relaxed
Jo	CW	449	459	253(C)	326(NC)	192(C)	217(NC)	L	L	L	L	Relaxed
$\bar{x}$		386	396	200	202	241	188					
Pa	CW	240	332	79(C)	31(C)	88(C)	65(C)	0	0	0	0	Key press
Ba	CW	424	701	208(NC)	278(NC)	184(C)	265(NC)	0	0	L	L	Key press
Ha	CW	172	292	64(NC)	97(NC)	88(NC)	128(NC)	0	0	0	0	Key press
At	CW	425	386	464(C)	304(NC)	525(C)	362(C)	0	0	0	0	Key press
$\bar{x}$		315	428	204	178	221	205					
$\bar{\bar{x}}$		351	412	202	190	231	197					
$t_{\bar{\bar{x}}}$		.98		.48		1.06						
$P_{\bar{\bar{x}}}$		>.05		>.05		>.05						

*NCR - Not Continuous and Reversing
‡C - Continuous
#NC - Not Continuous

tend to look left and in the 270-degree stop position would tend to look right. Hence the 90-degree stop position would facilitate left-beating nystagmus (produced by the CW deceleration) and the 270-degree position would facilitate right-beating nystagmus (produced by the CCW deceleration). Counterrolling involving horizontal eye movements relative to the skull, i.e., movements in the coronal plane, would of course be confounded by voluntary oculomotor control; and therefore only a tendency to counterroll the eyes in this plane would be expected. Results at the 90-degree and 270-degree positions are consistent with this explanation. If this counterrolling is attributable at least in part to otolith function, then we have the basis of an otolith modulation of cupula-initiated nystagmus responses. The likely direction of gaze in the 180-degree and 0-degree positions is undetermined and hence, expected results in these positions cannot be estimated from this hypothesis.

The additional observational conditions introduced in Experiment II, e.g., recording of positional nystagmus and recording of nystagmus during constant velocity around the horizontal axis, failed to provide insight as to the lack of correspondence between predicted (Figure 1) and obtained results in Experiments I and II. Only two of sixteen subjects (Bo and Be) showed positional nystagmus which would differentially affect nystagmic outputs for head-stop comparisons. In the case of Bo, it appears that the positional nystagmus might have interacted with the post-rotary nystagmus, but Be's response was opposite that predicted by a positional nystagmus influence. It is noted, however, that Bo's positional nystagmus observed during static testing revealed itself during constant velocity rotation about the horizontal axis. The direction and incidence of the reversing continuous nystagmus during constant velocity rotation exactly corresponded to the static positional nystagmus.

Also, from the data presented in Table II, the magnitude of nystagmic output following deceleration from horizontal-axis rotation does not appear to bear any correlation to the type of nystagmus (continuous or not continuous) produced during rotation which, in turn, does not seem to be influenced by the mental state of the subject.

The mental state or mental task assigned the subject, however, does seem to influence the incidence of sickness during rotation about the horizontal axis. In Experiment I where the subjects were required to attend to and report their body sensations, 33 per cent of the subjects requested to withdraw from the study because of severe nausea and of those who continued, 50 per cent reported nausea and stomach awareness. Sickness was also encountered in an earlier experiment (5) which involved even less exposure to horizontal-axis rotation but the same mental task. In contrast, subjects in Experiment II were required either to press a pushbutton or to completely relax during rotation; only 12 per cent reported stomach awareness, and none wished to discontinue the experiment. That assigned mental tasks may influence the amount of sickness during unusual vestibular stimulus is also supported by previous experimental results (6) and has been suggested by Wendt (12, p. 1207).

In Tables I and II, it is noted that large differences existed between nystagmic output following deceleration from rotation about the horizontal axis as opposed to vertical-axis rotation. The lowered nystagmic output following horizontal-axis rotation has been noted previously and attributed to conflicting sensory input between the canalicular and otolithic systems (5). However, in the earlier study (5) a suppression in nystagmus during constant velocity was observed as the subject moved through the nose-up position (0 degrees) which happened to be the only stop position used in that study. The present experiments show that the suppressed nystagmic output following horizontal-axis rotation occurs regardless of the final stop position. This points strongly to a suppression of canalicular influx by conflicting sensory input from other receptors, since, irrespective of stopping position, deceleration responses from horizontal-axis rotation were suppressed as compared with vertical-axis rotation. These observations, coupled with the higher incidence of sickness following horizontal-axis rotation and the correspondence of a static reversing type positional nystagmus and nystagmus produced during constant velocity rotation about the horizontal axis, point not toward a gravity-canalicular interaction directly, but, as others (3,5,7,8) have postulated, to a canalicular nystagmic response which is modulated by otolithic sensory input or other gravity sensitive receptors.

REFERENCES

1. Aschan, G., Bergstedt, M., Drettner, B., Nylen, C. O., and Stahle, J., The effect of head-movement on positional nystagmus; electronystagmography with an electric driven posture-table. Laryngoscope, 67:884-893, 1957.

2. Bergstedt, M., Studies of positional nystagmus in the human centrifuge. Acta otolaryng., Stockh., Suppl. 165, 1-144, 1961.

3. Chilow, K. L., Ueber den Funktionszusammenhang des Otolithenapparates und des Bogengangsystems. Z. Hals.- Nas.-u. Ohrenheilk., 17:485-494, 1927.

4. Collins, W. E., and Guedry, F. E., Arousal effects and nystagmus during prolonged constant angular acceleration. Acta otolaryng., Stockh., 54: 349-362, 1962.

5. Guedry, F. E., Jr., Orientation of the rotation-axis relative to gravity: Its influence on nystagmus and the sensation of rotation. BuMed Project MR005.13-6001 Subtask 1, Report No. 96 and NASA Order No. R-93. Pensacola, Fla.: Naval School of Aviation Medicine, 1964.

6. Guedry, F. E., Jr., Visual control of habituation to complex vestibular stimulation in man. Acta otolaryng., Stockh., in press, 1964.

7. Holsopple, J. Q., Factors affecting the duration of post-rotation nystagmus. J. comp. Psychol., 3:283-304, 1923.

8. Klestadt, W., Handbuch der Neurologie, Von Bunke-Foerster, Bd. IV, 591. J. Springer, Berlin, 1936. (Cited in Jongkees, L. B. W., On positional nystagmus. Acta otolaryng., Stockh., Suppl. 159, 78-83, 1961.)

9. McLeod, M. E., and Correia, M. J., Use of caloric test in evaluating the effects of gravity on cupula displacement. BuMed Project MR005.13-6001 Subtask 1, Report No. 94 and NASA Order No. R-93. Pensacola, Fla.: Naval School of Aviation Medicine, 1964.

10. Steinhausen, W., Über die Beobachtung der Cupula in den Bogengangsampullen des Labyrinths des lebenden Hechts. Pflüg. Arch. ges Physiol., 232:500-512, 1933.

11. Egmond, A. A. J. van, Groen, J. J., and Jongkees, L. B. W., The mechanics of the semicircular canal. J. Physiol., 110:1-17, 1949.

12. Wendt, G. R., Vestibular functions. In Stevens, S. S. (Ed.), Handbook of Experimental Psychology. New York: John Wiley and Sons, Inc., 1951.