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SUMMARY PAGE

THE PROBLEM

During travel to the Moon and Mars, as well as on the surface of these celestial bodies, man will be exposed to magnetic fields considerably lower in intensity than that of the geomagnetic field. The present study is a continuation of a previous investigation of the physiological and psychological effects of low intensity magnetic fields.

FINDINGS

Four volunteers exposed to an experimental magnetic field of 50 gamma field strength (1 gamma = 10^{-5} gauss) for a period of ten days showed a significant gradual decrease of the scotopic critical flicker fusion (CFF) from which they recovered a few days after exposure. Two control subjects confined in the geomagnetic field for the same period of time showed no change in CFF.

ACKNOWLEDGMENTS

Grateful acknowledgment is made to the six volunteers who served with patience and complete cooperation in this prolonged experiment.

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INTRODUCTION

The magnetosphere is an intrinsic component of the Earth environment, and travel beyond this sphere will expose man to near absence of a magnetic field. A new look at the Earth's magnetic field (1) reveals a teardrop shape of the magnetosphere formed under the influence of the solar wind. The boundaries of the geomagnetic field towards the Sun terminate in approximately 10-Earth radii distance from the Earth, and the tail extends away from the Sun, probably more than halfway to the Moon. During solar quiet periods manned spaceships on their way to the Moon or Mars will be exposed during most of their travel to the interplanetary magnetic field with a field strength of less than 10 gamma (1 gamma equals 10^{-5} gauss) (2). The immediate magnetic environment of the crew will have a somewhat higher intensity than that of the interplanetary field, depending on the magnetic properties of the craft and its equipment and on magnetic fields generated by on-board electrical circuits. No experimental measurements of magnetic fields inside a manned spacecraft under space simulating conditions have yet been made.

Tentative estimates based on recent measurements are available on the magnetic environment of future destination sites on the Moon, Mars, and Venus. During approach to Moon impact (3) and during flyby of Mars (4) and Venus (5) no magnetic fields comparable to the geomagnetic field were detected. The magnetic field strength close to the surface of these celestial bodies is most likely below 100 gamma. Slightly higher fields may be encountered on the surface where rocks may have retained remanent magnetism possibly induced by high solar magnetic fields during the cooling process of these celestial bodies.

The near absence of a magnetic field in extraterrestrial travel presents at least two kinds of possible hazards. One of these has long been recognized and concerns an increase of mutation rate due to cosmic radiation in the absence of a shielding magnetic field. On a terrestrial scale the Van Allen belts with their accumulation of electrons and protons are an impressive demonstration of the shielding effect of the geomagnetic field. This shielding is added to the absorption of cosmic radiation in the Earth's atmosphere. With both these natural effects absent around a space vehicle, artificial means of protection against cosmic radiation have to be devised to avoid genetic damage.

The second kind of a hazard has been pointed out recently (6) and suggests a possible direct physiological effect of the near absence of a magnetic field beyond the magnetosphere. It is hypothesized that the presence of a magnetic field during the major part of the development of life on Earth has played a certain role in development and that living beings probably cannot be removed from the geomagnetic environment without penalty.

For experimental purposes an environment with a field strength below 100 gamma should reasonably simulate magnetic conditions in interplanetary flight as well as those encountered during approach and landing of the spacecraft. In a previous report (6) from this laboratory the results of exposure of two healthy male subjects to a magnetic field of 50 gamma generated by a coil system were described. It was found that the results of most of the physiological and psychological tests performed were not influenced by the magnetic field conditions. However, strong indications pointed to a decrement of the peripheral critical flicker fusion frequency during the period of absence of the geomagnetic field.

These observations formed the stimulus for repetition of the experiment, using different subjects and additional as well as improved testing procedures. Again, in all subjects studied the peripheral critical flicker-fusion frequency diminished gradually during the exposure period and recovered rapidly to pre-exposure levels during the post-exposure period. These findings indicate that in the low magnetic environment, some physiological processes deviate from the norm in the geomagnetic field.

LOW FIELD ENVIRONMENT

The same coil system as in a previous experiment (6) was used in the present study. This system at the Naval Ordnance Laboratory, White Oak, Maryland, furnishes magnetic fields of very low field strength in regions of comparatively large volume. The cubical coil system consists of three mutually perpendicular series of square Helmholtz coils with a side length of 28 feet each. By an appropriate electrical current in the coils the Earth's field can be reduced in the center of the system to a value close to zero. Away from the center the field increases gradually and reaches about 100 gamma in the corners of the 8- by 8- by 8-foot experimental room co-centered within the coil. In the space occupied by the subjects the field was not higher than 50 gamma, with a gradient of about 10 gamma per foot. This experimental field probably does not deviate much from the magnetic field on the surface of the Moon, and the weak lunar field in proximity to the surface may even have a similar gradient due to local ferromagnetic formations.

In the first experiment (6) the three separate power supply systems for the vertical, north-south and east-west cancellation of the Earth's field were manually regulated, but, in the present one an automatic regulator was used. Noise and ripple of this automatic system were less than one gamma. The indicators of three FM 204 Foerster magnetic field measuring instruments operated at a sensitivity of 1 gamma per scale-division and positioned in the center of the coil system did not deviate noticeably from the zero position during the ten-day exposure period. This indicates that during this period, the center of the field was held below one gamma in spite of the daily periodic changes of the Earth's field and the temperature induced resistance changes of the compensating coil system. A check with the Fredericksburg Magnetic Observatory, Corbin, Virginia, indicated that during the duration of the experiment, the geomagnetic field was quiet and free of magnetic storms.

The space occupied by the two control subjects was located fairly close to the coil system. Measurements of the field strength in the control space during times of activation of the coil system indicated only small deviations from the geomagnetic field. The highest value of the field in the control room was 600 millioersted compared with that of 535 millioersted at a distance of 50 feet from the coil system. For all practical purposes the men lived for the total time in the geomagnetic field.

At the time of the present experiment (April 1964) the Naval Ordnance Laboratory coil system was the largest system of this kind available in the United States. Since then Goddard Space Flight Center, Greenbelt, Maryland, has built a system in which three subsystems enclose a sphere about 40 feet in diameter. This system not only is able to cancel automatically the geomagnetic field but also can provide a rotating magnetic field vector of desired strength which may provide interesting experimental conditions for future physiological studies.

Another means of generating a field-free room should be mentioned here briefly. A room shielded by one or several spaced layers of mumetal or a similar alloy of high magnetic permeability can provide a magnetic environment with a field strength of below 100 gamma. The gradient of the magnetic field in such a room is usually smaller than the gradient in a coil system. However, confinement in such a room will be felt by the subjects more than in the wide open coil system. It should be most interesting to compare possible physiological effects in the coil with those in the shielded room and bring these in relation to the norm in the geomagnetic field.

PROCEDURE

SUBJECTS

Six healthy subjects, naval enlisted men 17 to 19 years of age, served as subjects. General clinical findings obtained 20 days prior to the experimental period are summarized in Table I and show good to very good general physical fitness.

Four of the subjects (DT, RT, AL, OV) were continuously exposed for ten days in an activated Helmholtz coil system to a magnetic field about one thousandth of the Earth's magnetic field. The confinement of these subjects on an 8- by 8-foot platform in the center of the coil started six days before and ended five days after actual magnetic exposure. Thus, self-control values from the four subjects were available on the physiological and psychological tests given throughout the experimental period. The second group of two subjects (PO, WH) were confined during the same period of 21 days to an area of 64 square feet just outside the coil system in the geomagnetic field. The regimen (food, sleep-wake and work cycles, etc.) was the same for these two groups, and wherever possible the same tests were given to both groups. The normal test period extended from 8 in the morning til 4 in the afternoon, with occasional evening sessions. Usually, the two control subjects and two from the experimental group were tested at the same time by different experimenters using methods with a minimum of interference. The experimenters were assigned to tests of their specialty, and little switching of testing personnel from test to test took place.

Apparatus and time limitations necessitated certain deviations in the testing procedure for the two groups. Some equipment used in the geomagnetic field was not

Table I

General Clinical Findings on Subjects Tested

Twenty Days Prior to Experimental Period*

Subj.	Age Weight (lbs) Height (in.)	Past Hist.	Phys. Exam. B.P. (mm Hg)	X-ray Chest	Blood Morph. Hemat. PBI	Serum Cholestrol ECG	Urine Chem. Micro	Gen'l. Fitness
DT**	19 167 72	Not sig.	N-L*** 110/60	N-L	N*** 49 4.1	113 N-L	N N	Very Good
RT**	19 129 70	Not sig.	N-L 120/50	N-L	N 46 4.1	132 N-L	N N	Very Good
AL	18 132 65	Not sig.	N-L 132/78	N-L	N 47 4.1	130 N-L	N N	Good
OV	18 140 69	Cardiac Arrhyth.	N-L 106/70	N-L	N 49 4.4	175 N-L	N N	Good
PO	19 146 68	Not sig.	N-L 110/70	N-L	N 46 5.1	184 N-L	N -	Very Good
WH	17 142 67	Not sig.	N-L 122/74	N-L	N 47 3.9	169 N-L	N -	Good

*Each value is a single finding of the examining physician

**DT and RT are brothers

***N = Normal   N-L = Normal Limits

clean enough magnetically to be introduced into the coil system. Other equipment was permanently mounted inside the coil and could not be used for the group outside. Even though the full value of a separate control group outside the coil system could thus not be realized, the fact that the four subjects in the coil system served as their own control furnished sufficient reference data.

The present study of the effects of a null magnetic field may be conveniently arranged under three headings: 1) clinical tests, 2) visual tests, and 3) psychophysiological tests. The visual tests are separated by special heading from the clinical tests since pilot experiments had indicated a special sensitivity of the visual system to low magnetic fields.

CLINICAL TESTS

The body weight of the four experimental subjects was determined on two different days before, and three different days after exposure to the null field. The control subjects were weighed on the same days. Blood pressure and other vital data were determined daily, shortly after awakening. A sphygmomanometer modified by replacement of ferromagnetic parts was used for blood pressure measurement. Pulse rate was obtained by palpating the radial pulse, and body temperature by an oral thermometer. Counts of chest movement rendered the respiratory rate which was also noted on the electrocardiographic tracings. Eosinophils were counted by differential blood count of the smear and by direct counting chamber technique.

The electrocardiogram (ECG) was recorded on a Sanborn 8-channel recorder in combination with a Sanborn 7-channel tape recorder. The instruments were placed well outside the coil system. Vectorcardiograms were obtained with the Frank lead system (7), but the position of the H-electrode was changed from the neck to the forehead. All recordings were made with the experimental subject at rest, sitting in a chair inside the confinement of the experimental platform, while the controls were sitting in their area in the geomagnetic field. With a few exceptions measurements were made in mid-morning of each day. From these ECG's the heart rate was determined using the mean of ten measurements of the R-R interval. The tape recordings of the orthogonal V_x, V_y, and V_z traces were later used as input to an oscilloscope to demonstrate and photograph the planar electrocardiogram loops in the frontal, horizontal, and left saggital planes. The average maximum spatial T-wave vector was calculated from the three orthogonal values. These vectors of the four experimental subjects were used in a Student t-test of significance to determine the probability of possible differences between the means found during the exposure period and the means of the pre- and post-exposure periods.

The electroencephalogram (EEG) was recorded on a Sanborn 8-channel recorder in combination with a Sanborn 7-channel tape recorder. Both instruments were placed well outside the low magnetic field. The subject was sitting at rest with eyes closed within the range of his confinement and under average room lighting and noise conditions. Measurements on the experimental and control subjects were made every other day in the midmorning. The C-101 electrodes by Lexington Instruments, Waltham, Massachusetts, with a core of silver chloride were used. Contact with the subject's scalp was established by Sanborn Redux electrode paste. Three electrodes were placed by means of Velcro straps on the following positions: 1) 3 centimeters to the left of the inion (external occipital protuberance), 2) 6 centimeters superior to the inion and 3 centimeters to the left of the mid-cranial line, and 3) on the vertex.

The EEG records were analyzed for the frequency distribution in the 8- to 36-cps range. The wave lengths in about 20 one-second periods of predominant alpha rhythm were measured and the corresponding frequencies calculated. Frequency distribution curves were plotted for each subject and each day of tests. In addition to the visual inspection of the frequency distribution the data of each measurement were classified in three groups: 1) alpha (3-13 cps), 2) intermediate (14-17 cps), and 3) beta waves (15-45 cps), and for each group the percentage of the total number of waves during the same period of time was calculated. A Student t-test of significance was made to determine if the data from each subject determined during the exposure period belonged to the same population as the pre- and post-exposure values.

With the electrodes remaining in place from previous EEG measurements the response to bright flashes (evoked potential) was then recorded. The EEG signal from the bipolar electrodes was monitored by a Sanborn 350 recorder and amplified by a Sanborn 350-270 V high gain pre-amplifier. The amplified signal was fed into a Computer of Average Transients (CAT), Model 400B. A Grass PS2 photostimulator was used to regulate the intensity and intervals between flashes and to trigger the CAT's memory circuits. The light flash had an approximate intensity of 75,000 candles at 9 feet from the lamp, a duration of 10 microseconds, and a flash interval of 1 second. The CAT was allowed to accumulate 100 cortical evoked traces with a duration of 0.5 second each. The summated evoked potential was recorded on a Moseley X-Y recorder. At each recording session three records were made; the first, with flash covered and the second and third with open flash.

The audiogram was determined with a Rudmose Automatic Audiometer (Model ARJ-4). Measurements on the four experimental subjects were made on two different days before and two after the exposure period. The two control subjects were tested on the same days.

RESULTS

The results of the clinical tests, shown in Table II, were essentially negative: Most of the measurements from the four subjects during exposure to a null magnetic field did not deviate from the values determined during the pre- and post-exposure periods. In addition, these values did not deviate significantly from the corresponding ones obtained from the two control subjects in the geomagnetic field. However, some changes which have been attributed to the effects of confinement for a period of 21 days should be noted.

Table II

Results of Clinical Tests During 21-Day Experimental Period

Tests	Pre-Exposure (Days 1-6) N**	Mean	S.D.	Per-Exposure (Days 7-16) N	Mean	S.D.	Post-Exposure (Days 17-21) N	Mean	S.D.
Four Experimental Subjects*									
Systolic blood pressure (mm Hg)	24	109	8	40	106	8	20	101	6
Diastolic blood pressure (mm Hg)	24	67	6	40	68	7	20	68	7
Pulse rate (beats/min)	24	63	6	40	64	7	20	61	6
Respiratory rate (breath/min)	24	15	3	40	16	3	20	16	2
Oral temperature (°F)	24	97.2	0.7	40	97.1	0.5	20	96.9	0.4
Body weight (pounds)	8	144	15				12	147	15
Eosinophils	12	160	45	20	154	60	12	133	60
Two Control Subjects*									
Systolic blood pressure (mm Hg)	12	114	6	20	116	10	10	117	10
Diastolic blood pressure (mm Hg)	12	73	6	20	75	9	10	78	6
Pulse rate (beats/min)	12	65	11	20	67	8	10	67	8
Respiratory rate (breath/min)	12	13	3	20	15	3	10	18	2
Oral temperature (°F)	12	96.6	0.5	20	96.9	0.5	10	96.9	0.4
Body weight (pounds)	4	144	3				6	149	2
Eosinophils	6	225	40	10	230	20	6	235	20

*The experimental subjects only were exposed for 10 days to a substantially zero magnetic field; all subjects were confined for the 21-day period.

**N = number of measurements

An increase in mean body weight was observed in the previous experiment (6) and was again seen in all six subjects of the present study; the greatest increase was observed in all subjects at the end of the first five days of confinement. No correlation of the pattern of the weight increase with the experimental magnetic field condition could be determined.

Diastolic blood pressure remained essentially unchanged in all subjects during the total confinement period. Systolic blood pressure did not change in the two control subjects. However, progressively lower mean systolic values were obtained in the experimental subjects; there was a decrease of 8 mm Hg between the mean pre- and post-exposure values. The steady decrease over the total period of 21 days suggests an effect of confinement rather than that of the null magnetic field on the systolic blood pressure.

In all subjects the mean pulse rate, measured in the early morning, did not change appreciably nor did the mean eosinophil count, but there was an increase in mean respiratory rate.

The heart rate (not shown in Table II) determined from the ECG recorded in mid-morning after the subjects had been active for a few hours showed a continuous increase for all six subjects. The mean rise in rate over the 21-day period was 20 beats per minute or approximately 1 beat/minute per day. Since such an increase was seen in all subjects, it cannot be attributed to magnetic field effects; it thus appears to be an effect of confinement only.

The mean oral body temperature of the four experimental subjects seems to show a slight trend to lower values; this was not observed in the two control subjects. Since the decrease in the experimental subjects extended over the total period of confinement it appears to be a confinement effect.

The vectorcardiograms of the four experimental subjects showed no obvious effect of the low magnetic field exposure. The statistical analysis of the spatial T-wave vector for possible null field effects on direction or magnitude rendered negative results. However, the range of the maximum spatial T-wave vector narrowed slowly over the total confinement period of the experimental subjects as well as the control subjects. The mean decrease in all six subjects was 20 per cent of the original values and was considered a confinement effect.

The wave frequencies of the electroencephalograms of the experimental subjects seemed in general not to be influenced by the null field exposure. However, the EEG of one subject (DT) showed a significant increase in the mean percentage alpha waves from 90 in the geomagnetic field to 95 in the null magnetic field ($p<0.05$). A decrease in the mean percentage of beta waves from 5 to 2 per cent was observed in the same subject ($p<0.05$).

No effect of the experimental condition of a low field on the cerebral response to bright flashes of light (evoked potential) was observed in evaluation of the records of the stimulated EEG. Neither was a confinement effect on the evoked potential observed.

The audiogram showed no effect of the exposure of the four experimental subjects to a null magnetic field; in no record of any subject was a confinement effect noted.

VISUAL TESTS

Visual Field: An automatic perimeter was designed and built to probe the visual field objectively by programmed light flashes guided from a central source to the visual perimeter by fiberoptics. Experimental difficulties were experienced with this instrument; therefore, the visual field was explored in the classical way using a meter tangent screen. Test objects (1/1000 and 2/2000) were moved centripetally towards the point of fixation along the vertical and horizontal, as well as two intermediate points. Both eyes were tested and the plots on standardized forms evaluated with a polar planimeter. Tests of the experimental subjects were made only on two different days during the late exposure as well as the post-exposure periods. The control subjects were tested on the same days.

Visual Digit Span: A series of ten 4-, 5-, and 6-digit numbers were flashed for a 0.01-second period on a screen 10 feet from the subjects. The subjects recorded the numbers between flashes. Weighted scores of 1.0, 1.8, and 3.6 were given for each correct reproduction of the 4-, 5-, and 6-digit numbers, respectively. The total weighted scores served as a measure of the visual digit span for each session.

Absolute threshold of dark adaptation was determined for the central part of the retina as well as for the whole retina (integral dark adaptation) by use of the Goldmann-Weekers Adaptometer (Haag-Streit AG, Berne, Switzerland). The subject was light adapted for five minutes in a brightly lit sphere (3000 Lux). After switch-off of the bright light he signaled at certain time intervals when he recognized a centrally fixed test plate gradually reduced in light intensity by the experimenter. A record of the absolute threshold of perception in the course of dark adaptation of the central part of the retina was gained by this procedure. In tests of the dark adaptation of the whole retina (integral dark adaptation) the subject indicated observation of the pulsating light of a given intensity which filled his total visual field during the course of dark adaptation. The records of both procedures were evaluated for light intensity at the absolute threshold of vision as well as for the light intensity at which cone vision passes into rod vision (alpha flex point). The control subjects were tested every second day during the 21-day period and the experimental subjects three times during the pre- and four times during the post-exposure periods.

Critical Flicker Frequency (CFF): Several methods were applied to determine the response of the subjects to flickering light. The necessity of excluding ferromagnetic material from inside the coil system required construction of special equipment. Conventional flicker fusion equipment was used outside the coil system on control subjects as well as on the experimental subjects during pre- and post-exposure periods.

1) The Strobotac method served to determine central and peripheral CFF. A standard Strobotac, Model 631-BL, General Radio Company, was modified as described earlier (6). A dense filter paper placed over the diaphragm in front of the lamp formed a flickering source of 2 inches in diameter and of 25-foot-candle brightness which was observed by the subjects from a distance of 10 feet. Thus the object subtended a visual angle of 57 seconds. Measurements were made in the evening in a moderately illuminated room, with the flickering light source presented on a black cloth background. The central flicker to fusion and fusion to flicker threshold was determined by ten single measurements in each direction, with observation of the flickering source by the right eye while the left eye was occluded by an eye patch.

For the determination of the peripheral CFF by this method the subject fixated a small light source placed at a horizontal distance of 130 cm from the Strobotac (visual angle at 10-feet viewing distance 23° 25'). The surroundings of the two light sources were occluded by a background screen of black cloth. All subjects were tested every second day by the central and peripheral method.

2) A tube tester (C481C), CGC Medical Electronics Corporation, Hempstead, Long Island, was used which operates a Sylvania tube (R1131C) as flickering light source. For the present purpose a light-dark relationship of 1:1 and a tube current of 20 mA were selected. The control subjects were tested every second day during the total period and the experimental subjects on five different days before as well as after the exposure to the null field. The tube was ferromagnetic, and the test could not be applied in the activated coil system.

3) Rotating disk tester: Special equipment which contained a rotating disk to generate a flickering light signal was constructed to measure central photopic as well as peripheral CFF. Figure 1 is an over-all view and Figure 2 a schema of the arrangement. The subject sat just inside the limits of the 8- by 8-foot experimental platform with his head held in firm position by a dental bite plate. He faced a large screen (99.06 x 132.08 cm) subtended 34° 25' in the vertical direction and 41° 50' in the horizontal direction at the 147.5-cm viewing distance. In measurements of photopic CFF a beam splitter prism placed 15 mm in front of the subject's right eye allowed the experimenter to project a light spot on a selected part of the retina. In measurements of central flicker fusion the light spot was modulated at selected frequencies by a disk rotating at measured speed. The intensity of the flickering light was controlled by a regulated source and filters. Brightness measurements were made at the test position of the eye and near the source by means of a Macbeth illuminometer. The screen which formed the background for the light spot was illuminated to match the intensity of the flickering spot. Retinal illumination from -1.4 to 3.6 log Trolands was used. The subject's right eye was dilated approximately fifteen minutes prior to each test period, rendering his pupil throughout the test session substantially larger than the effective size of the artificial pupil of 2 mm diameter. The subject entered the dark test enclosure about ten minutes before the test which started at low intensity with a frequency well above perception of flicker. The rate was then slowly lowered until first appearance of flicker was reported by the subject. The threshold measurement was

taken at least five times for each luminous intensity used in the test sessions. This test series was performed every second day of the 21-day period with the four experimental subjects only.

The scotopic critical flicker frequency was determined with basically the same arrangement. The large screen served now as flickering light source. The screen was homogeneously illuminated from behind by filtered light from a 15-watt source which was modulated by a rotating disk. Throughout the experiments the light intensity of the screen as viewed by the subject was just below one thousandth millilambert, which placed the screen in the range of human scotopic vision. The light intensity was determined by comparison of the large screen with the test plate of the Goldmann-Weekers adaptometer. The subject was dark adapted for thirty minutes, and the right eye used in the test was not dilated. Ten single measurements of the scotopic flicker fusion frequency were made during each session. The sessions were repeated every other day by all experimental subjects during the time they were in the coil system. Since an additional apparatus was not available, central and peripheral CFF as well as brightness discrimination could not be measured by this method for the control subjects.

Differential Brightness Threshold: The principle of the method used in this study is based on observations of blurredness of the retinal image by Fry (8) and as later applied by Miller (9) in a study of amblyopia. The contrast threshold of a narrow bar projected on the fovea depends on the width of the bar, and the narrower the bar, the more blurred the image becomes. For wider bars the contrast threshold is practically independent of the bar width. The critical width (angular subtense) of the bar at which further increases in size no longer decrease the brightness difference threshold was termed the index of blur by Fry (8).

The brightness threshold measurements were made with the same general arrangement as described for the flicker tests. A narrow illuminated slit was projected via a beamsplitter onto the retina, and the subject saw the slit on the background of the homogeneously illuminated large screen. The illumination of this screen, which was not changed during the entire series of experiments, had a value of 11.63 foot-candles. The light intensity of the slit was increased starting with the widest one (5.64 mm) by proper regulation of the light source and selection of filters until the subject first detected the slit appearing between markers on the large background screen. The width of the slit was then successively reduced in ten steps to the narrowest measure (0.65 mm). The differential brightness dB/B (brightness slit minus background/brightness background) does not change at first, but as the slit becomes narrower, its brightness has to be increased more and more to compensate for the increased blurredness of the slit image. The index of blurredness was determined graphically from the plots of the values of dB/B. The subjects were dark adapted for fifteen minutes before the test, but no eyedrops or artificial pupil was used. The measurements were repeated every second day during the entire 21 days with the experimental subjects only.

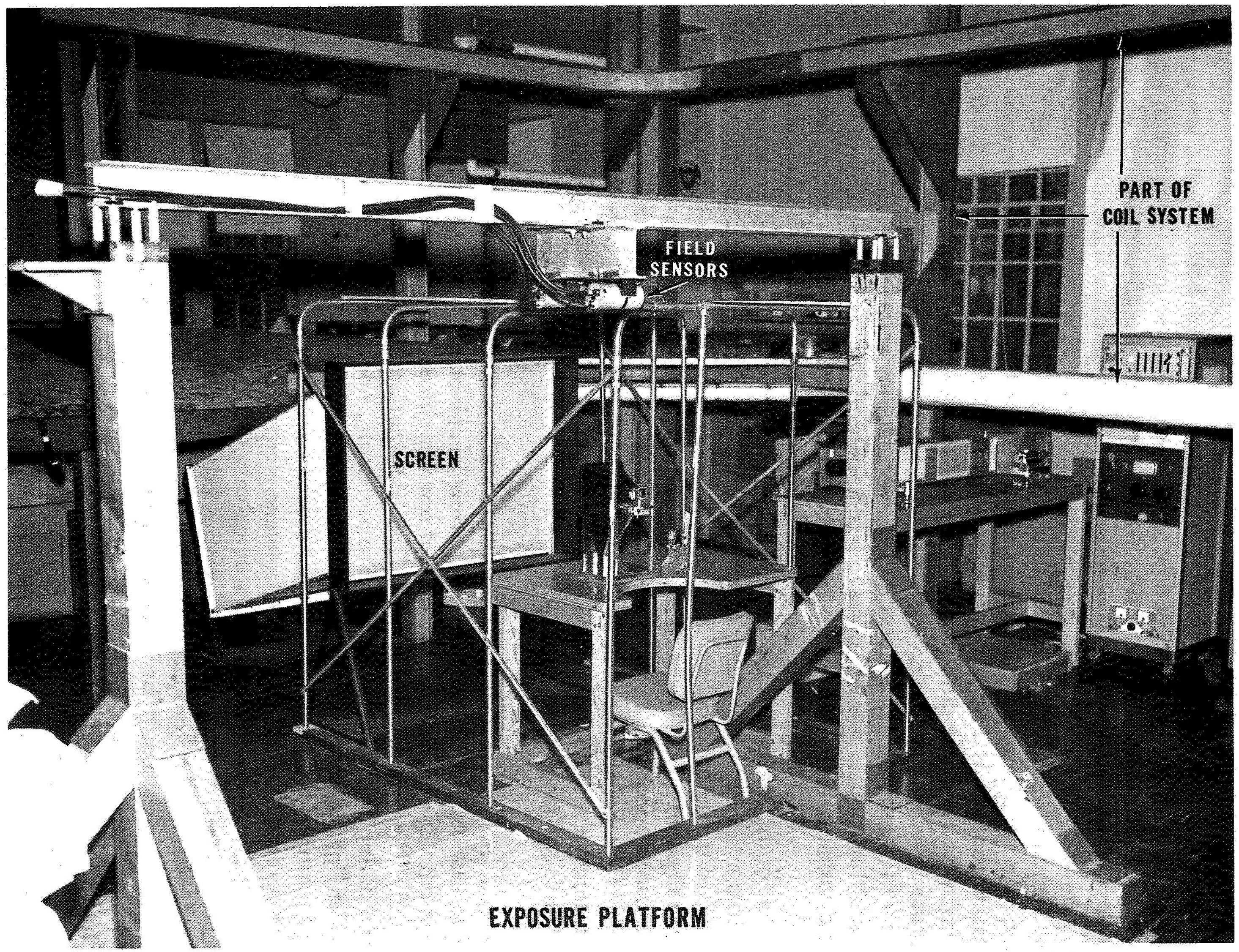

Figure 1

Arrangement for measurement of CFF and differential brightness threshold with black cloth screen removed from the measurement booth.

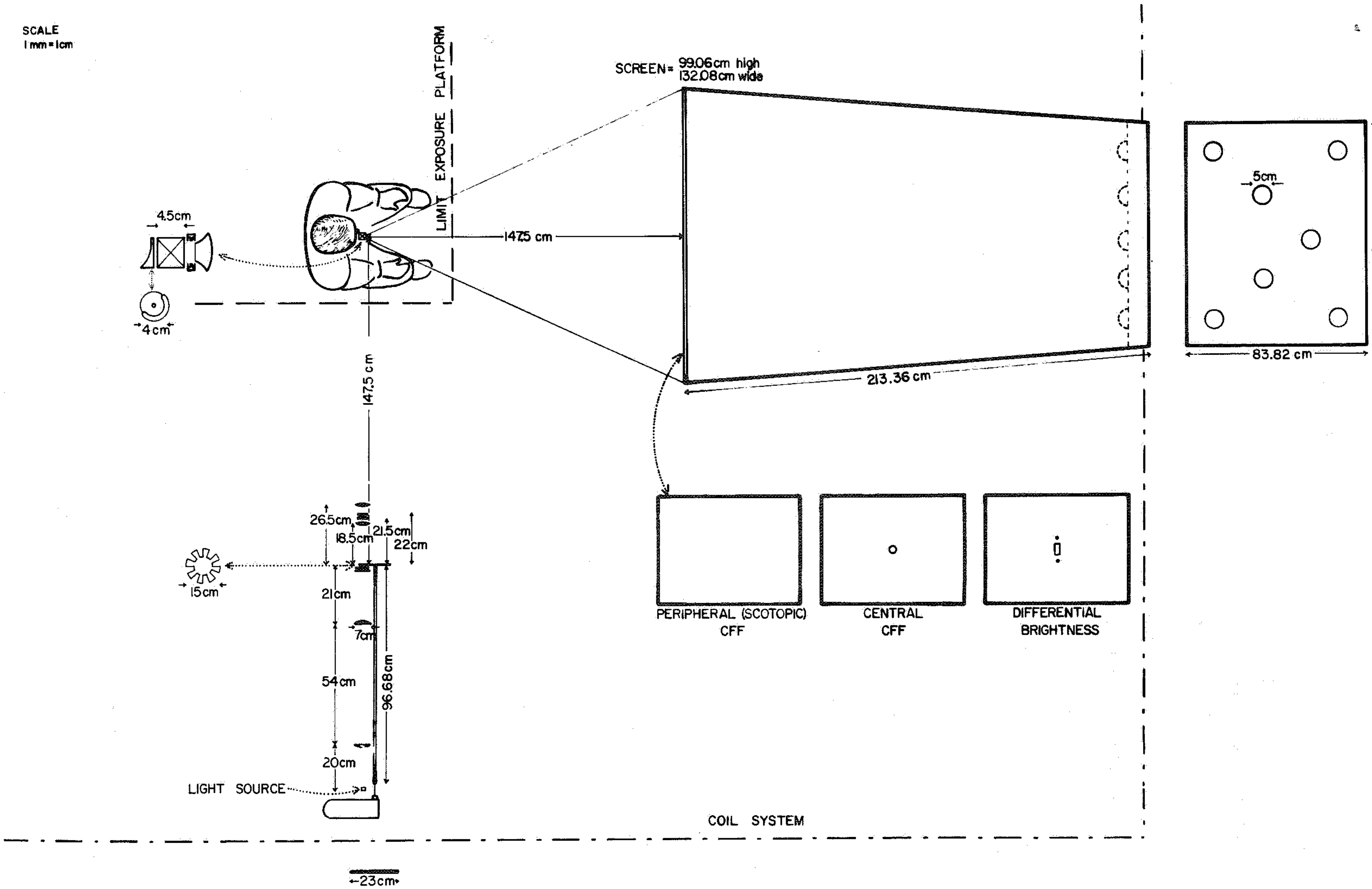

Figure 2

Schematic view of the arrangement depicted in Figure 1. This arrangement is used for measurement of 1) central CFF, 2) peripheral (scotopic) CFF, and 3) differential brightness.

RESULTS

Results of the visual tests were similar to those of the clinical tests in that they showed in general no unusual effects of the null field. However, as found in the earlier experiment (6), the peripheral CFF tests results included significantly lower values during exposure of the subjects to the null magnetic field. A similar effect was observed in experiments with scotopic flicker.

The area and extensions of the peripheral visual field of the experimental subjects were not changed by the transition from the null magnetic field to the geomagnetic field.

The two control subjects showed a uniform performance on the test of visual digit span during the entire period of confinement. The scores of the experimental subjects differed: One subject, OV, performed as steadily as the control subjects; two subjects, RT and AL, showed a learning effect, with scores improving during the greater part of the confinement period; and subject DT showed an irregular performance. However, in none of the experimental subjects could the score of the visual digit span in any way be connected to exposure to the null magnetic field.

The absolute threshold of dark adaptation and the alpha flex point showed little change in the two control subjects during the 21-day confinement period. The corresponding pre- and post-exposure values of the four experimental subjects were similar; with no data available for the exposure period itself the absence of a difference between these values indicates an absence of an effect of the null field on dark adaptation.

Critical Flicker Frequency: The results of the present study confirmed earlier observations of a significant effect of the null field on this visual function. Different experimental methods were applied in a probing effort to find the one which would show the greatest physiological reaction to the change of the magnetic environment; therefore, the findings should be considered in the light of such an approach. In addition, the ambiguity of CFF measurements suggested the use of the several methods.

Strobotac method, central observation: Over a period of 21 days the two control subjects each showed an average increase of 2 to 3 cps over the threshold starting value of 37 cps; this increase was attributed to the effects of confinement. None of the experimental subjects showed an increase of the threshold during the exposure period, but three of them (DT, RT, and OV) showed a delayed average increase of 2 cps during the post-exposure time. It appears possible that during exposure to the null field, the confinement effect which caused in the control subjects an increase of CFF was compensated in those three experimental subjects by a decrease of the threshold due to the magnetic environment. Thus, a depressing influence of the null magnetic field on the central CFF appears likely.

Strobotac method, peripheral observation: In the control subjects who spent the total time of 21 days in the geomagnetic field the threshold increased steadily during this period in one subject (PO) from 20.5 to 23.0 cps and in the other subject (WH) it stayed constant at 21 cps with small daily variations. The standard deviation of the measurements on any single day was about ± 1 cps. The strong increase after the sixteenth day described in the four experimental subjects was not observed in the two control subjects.

The results of the peripheral CFF measurements in the experimental subjects are plotted in Figure 3. For comparison the results of earlier measurements (6) obtained with the same method are reproduced in Figure 4. All six curves show a slow decline of the CFF frequency during the exposure period and a return to normal after restoration of the geomagnetic field environment. The post-exposure period is of special interest: The decline during exposure is sharply reversed, and after an overshoot in some subjects all subjects' values, a few days post-exposure, reached a frequency similar to the pre-exposure ones. The probability that the values measured during the later part of exposure belong to the population of values of the combined pre- and post-exposure periods was calculated and found to be less than 0.01 (t-test).

The method of testing produced occasional erratic readings (subject AL, for example, Figure 3) and large individual differences in the maximal decrease of CFF during exposure. Erratic readings were caused mainly by inconsistent fixation of the central light source.

Sylvania tube tester: The two control subjects showed a steady increase of the CFF threshold during the confinement period of 21 days as tested by this means. If a straight line were drawn through the daily scatter of values, the reading for the last day of confinement in both subjects would be 4 cps higher than that at the start of the experiment. This increase is most probably due to confinement.

Since the tube tester had ferromagnetic parts, measurements of the experimental subjects during exposure were not possible. However, in all four experimental subjects the post-exposure values were higher (3 to 5 cps) than the pre-exposure ones; this is comparable to the rise seen in the control subjects. The only indication of a possible magnetic effect can be derived from the observation that the values of the first measurements made ten hours after the geomagnetic field had been reinstalled were as low as the pre-exposure values in all experimental subjects and that the actual increase to final post-exposure values took place in the main during the first two days after exposure was terminated. This indicates that during exposure, the increase due to confinement was obviously compensated by a decrease of the CFF values due to the zero field exposure.

Rotating disk tester, central CFF: Results for this test and its scotopic variation are available solely for the experimental subjects since only one stationary apparatus was available. Light intensities from -1.4 to 3.6 log Trolands were applied. It was observed in all four subjects that the frequencies of fusion increased in a linear fashion from about 10 cps at -1.4 log Troland to about 70 cps, this maximum frequency being reached at 3.0 log Trolands. At higher light intensities, up to 3.6 log Trolands, the observed fusion frequency decreased by about 5 cps. The increase of fusion frequency was characteristic for an individual subject, but no significant difference was found

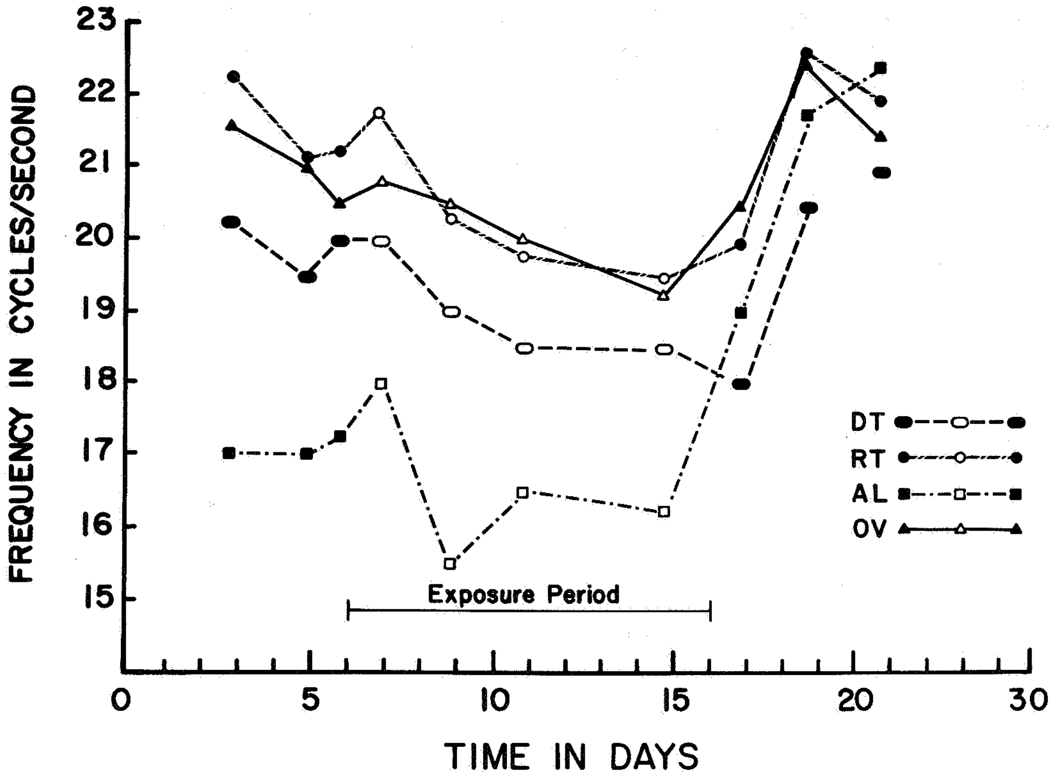

Figure 3

CFF data of four subjects measured by the Strobotac method with peripheral observation. (Standard deviation of data about ± 1 cps).

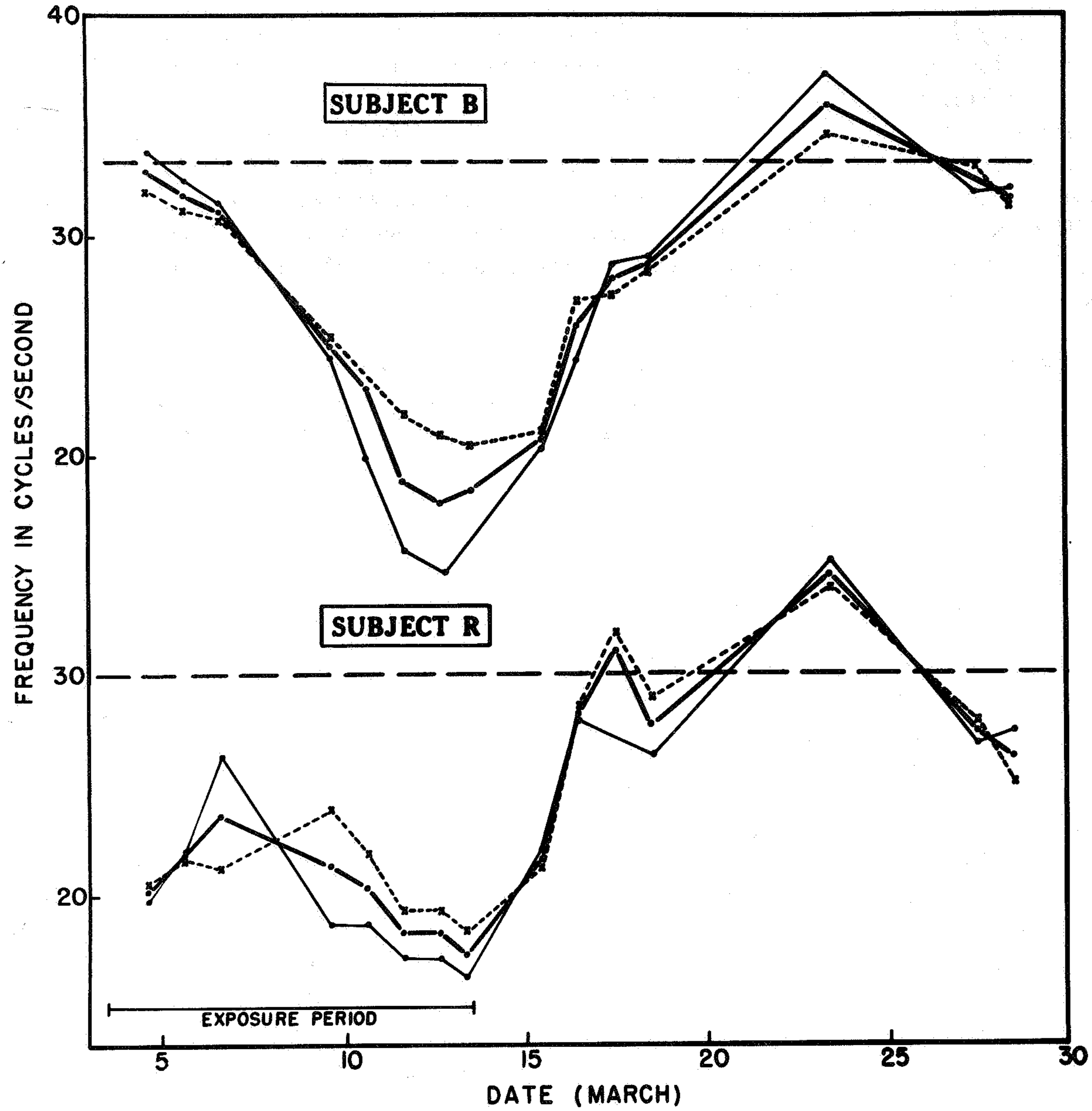

Figure 4

Reproduction of Figure 20 of reference (6). CFF data of two subjects measured by Strobotac method with peripheral observation. The darker solid lines represent medium values of the flicker fusion,and fusion flicker measurements depicted singly by dashed and light solid lines. The shape of the curves is the same as in Figure 3, but the effect of the null field is more pronounced.

between measurements made during the control periods before and after the exposure and the values observed during the exposure period.

Rotary disk tester, scotopic CFF: Detailed measurements on one subject (OV) are presented in Figure 5, and data from all four experimental subjects are shown in Figure 6. All subjects with the exception of DT showed a more or less gradual decrease of the threshold after exposure to the null field was initiated. Even though it does not appear that the CFF values of the other three subjects, RT, AL, and OV, reached a plateau towards the end of the exposure, the mean of the CFF values measured during the second half of the exposure period may be compared with the mean values obtained during the pre- and post-exposure periods. In these three subjects the difference of the means was statistically significant ($p<0.001$, t-test).

At the beginning and end of the exposure period measurements were made one hour before the field was switched and six to eight hours after the change. In both cases the changes were small and do not indicate an immediate effect of the null field or a fast recovery from the exposure effects.

The scotopic CFF values of subject DT changed little during the exposure period. At present this observation cannot readily be explained since DT's peripheral observation of CFF with the Strobotac method was similar to the other experimental subjects (Figure 3). However, the steady readings of subject DT, illustrated in Figure 6, exclude explanation of the decline shown by the other three subjects as an error of measurement by the apparatus or the observer.

Differential Brightness Threshold: No significant difference was observed in the index of blurredness measured in the pre- and post-exposure period compared with the index found during exposure. It is of interest that the subjects reported increasing difficulty in detecting threshold brightness levels with prolonged exposure to the null field. Identification of the first appearance of the slit, regarded initially as a relatively easy task, was reported at the end of the exposure period to be difficult, and the slit suddenly appeared "strong." A similar lack of any apparent transition in appearance of flicker with gradual changes in target interruption was also reported for the tests of CFF in which the steady field broke abruptly into coarse flicker.

PSYCHOPHYSIOLOGICAL TESTS*

An extensive battery of psychological tests assembled by Reitan (10) to investigate the psychological effects of brain lesions in human beings was used to detect possible adverse effects of a null magnetic field environment. The design of the experiment provided for pre- and post-exposure testing of the four experimental subjects and testing of the two control subjects on the same days. All six subjects were tested in Pensacola, Florida, during the week preceding the experiments in Silver Spring, Maryland, and retested there while still in confinement, the day after the four experimental subjects

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*These tests were performed by personnel of the Department of Neurology, Indiana University Medical Center, and evaluated by Dr. Reitan.

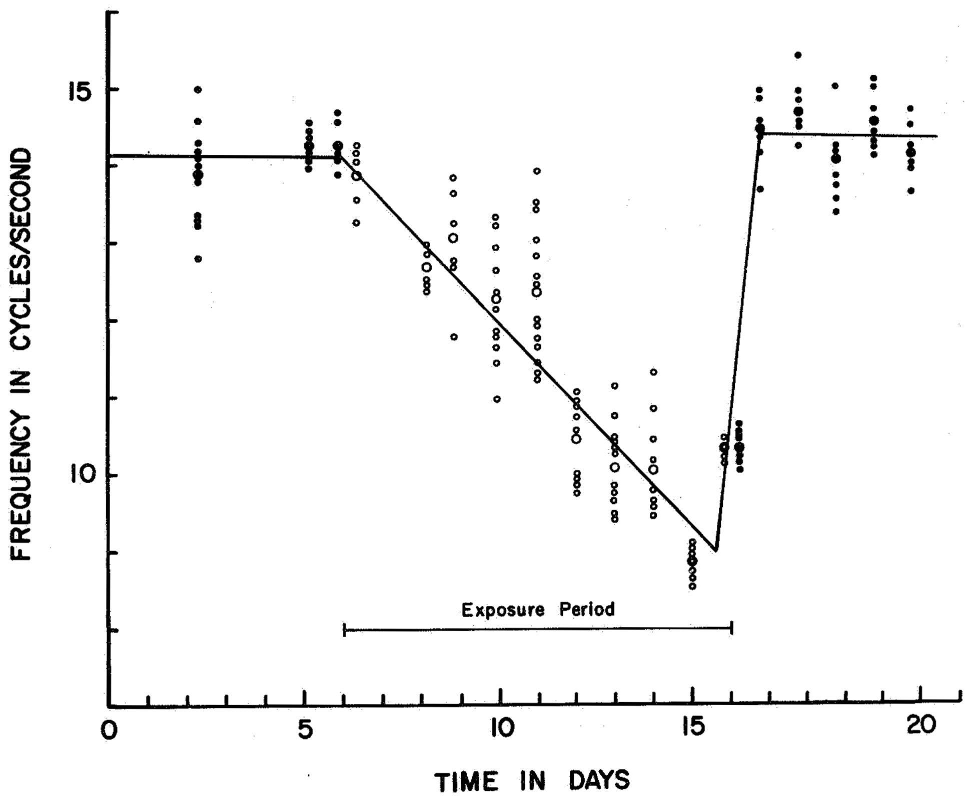

Figure 5

Scotopic CFF data of subject OV measured by rotating disk tester. Large dots represent means of single measurements. Standard deviation of measurements on any single day smaller than 1 cps.

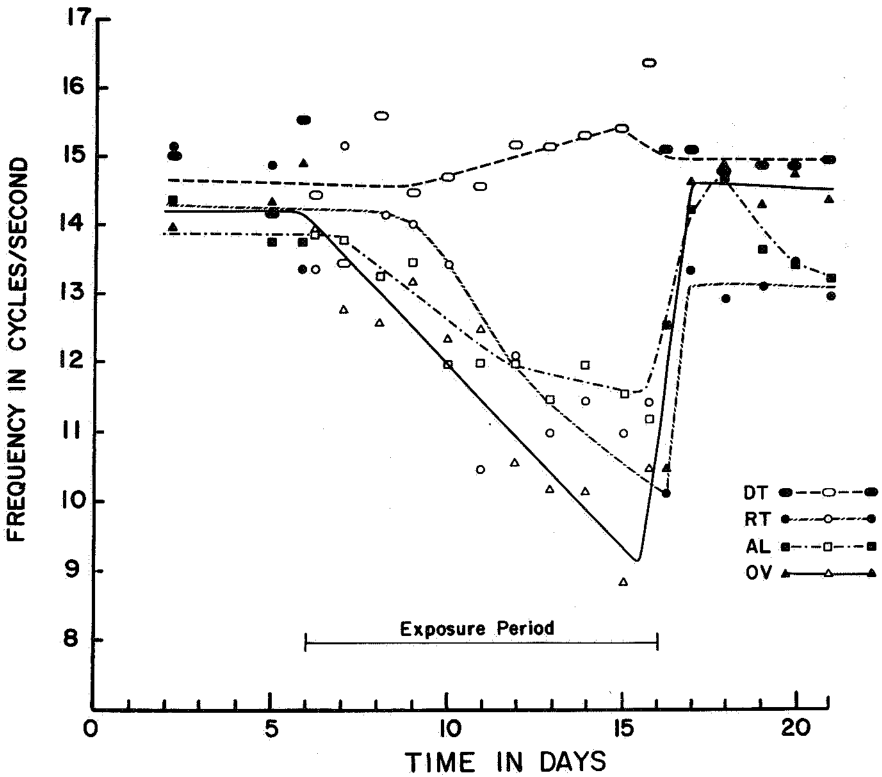

Figure 6

Scotopic CFF data of four subjects measured by rotating disk tester. With the exception of subject DT the scotopic CFF values decreased gradually during exposure to the null field and recovered to pre-exposure values in a few days after exposure had been terminated.

had finished the exposure period. The test battery included 1) general intelligence measures (Wechsler-Bellevue Scale); 2) measures specifically sensitive to impairment of cerebral functions (Halstead's battery of neurophysiological tests and a trail making test); 3) tests of perceptual and motor functions (grip; tactile, auditory, and visual imperception; astereognosis; finger agnosia); and 4) measures of emotional stability (Minnesota Multiphasic Personality Inventory).

None of the differences between pre- and post-exposure scores in the experimental subjects approached statistical significance, and no significant differences in the over-all performance of the experimental and control subjects was observed. Thus, the results provide no reliable evidence of adverse effects on the subjects of the ten-day stay in the near absence of a magnetic field environment in any of the four categories of psychological measurements.

DISCUSSION

Physiological effects of the geomagnetic field on man are not identified and for all practical purposes are assumed not to exist. In textbooks of ecology the magnetic field in our physical environment is not mentioned at all. Thus, at first glance complete removal of the geomagnetic field from the human environment appears to be insignificant, and no physiological changes should be expected. In the main, the results of the present study support this expectation. In most of the physiological and psychological tests performed no significant effects were observed, and the experimental subjects did not seem to notice any difference between the geomagnetic field and the field-free environment. Since a decrease in the fusion threshold of flickering light during exposure of the four human subjects to the null magnetic field was again observed, this discussion will concentrate mainly on an interpretation of the CFF findings.

In an earthbound laboratory, conditions for the generation of a magnetic field-free environment are limited. A space of 8 by 8 by 8 feet is at present an economically feasible limit for a field-free room, but this confines human subjects to a small area for a prolonged period of time, especially if long-term effects of the null field environment are to be investigated. Since confinement as such has certain well-known physiological and psychological effects, our study was also concerned with confinement effects as distinct from possible null field effects. The six subjects were limited for 21 days to an 8- by 8-foot platform, but had an unlimited view of a larger room and were in continuous communication with the investigators. Radio and television were also provided outside the coil system. Morale and motivation of the subjects in general were high during the total confinement period, and only short periods of apathy or belligerence were observed. Occasional complaints of headache were common among all subjects and in one case malaise and stomach awareness were noted.

Physiological effects of confinement on all subjects have been mentioned: Increased body weight, decreased systolic blood pressure, increased heart rate, and increased CFF. Under our confinement conditions these effects were small and were generally recognized in a series of data as a trend which persisted with the same sign over the total period of confinement. For example, the heart rate of all subjects increased over the total period of confinement by about 1 beat/minute for every day of confinement. In general, no break in this linear relationship was seen at or following cancellation or at reinstallation of the geomagnetic field. Scotopic flicker fusion data were the only physiological data in which a change in magnitude could be associated with the magnetic field change.

The results of flicker fusion tests plotted in Figures 3 to 6 show a gradual decrease after the null field was generated and an abrupt reversal at the time of return to the geomagnetic environment. The maxima of these changes are greater than one standard deviation of measurements made on a single day or the day-by-day variations of the mean CFF data observed during the control periods. The interpretation of flicker fusion results is somewhat difficult because almost anything in the human body can produce significant though small changes in CFF. In the present experiments the CFF alterations were so closely associated with the magnetic field changes that they strongly suggest effects of the null field.

Awareness of the subjects that the field was being changed on a particular day, with possible resulting apprehension and anxiety, could be considered as an alternate explanation of the observed alterations in CFF. The influence of states of anxiety on CFF has been investigated (11, 12), and a depression of the threshold has been observed in most cases. However, mental patients were used in those studies, and the reaction of the mentally stable, normal subjects observed in the present study can hardly be compared with the reaction of high anxiety patients. If a state of apprehension or anxiety had been present in the subjects of our study at any time, it should have been most marked in the first few days of exposure to the zero magnetic environment. However, a corresponding, immediate rapid decrease of CFF was not observed at that time. When geomagnetic conditions were restored, the subjects took little notice of this event and were not at all concerned since they had not noticed any effects of the null magnetic exposure. Yet, a rapid return to pre-exposure CFF values was observed following restoration of the geomagnetic field conditions. Thus apprehension and anxiety can reasonably be discarded as possible causes for the CFF changes. No physical or other psychological factors could be identified as responsible for the CFF findings. This leaves the null magnetic field as the only presently recognizable cause for the CFF observations.

At present no explanation for this phenomenon of depression of the CFF threshold in the absence of a magnetic field can be given. The slow development of the effect on CFF may indicate a gradual depletion of a substance which is crucial in the photoreceptor cell or in the conduction of the signal. An example may illustrate this line of thought. Young (13) reported that 9 to 11 days are required for the outer segment of the photoreceptor cell to be renewed. This is the time it takes for protein to migrate from the inner segment where it is formed to the outer segment where it serves in the visual process. If defective protein is formed during the null field exposure of the cell, an effect on vision will be noticed only after a matter of days. Restoration of normal conditions would also take several days. The similarity of the time periods characteristic for the diffusion process in the photoreceptor cell and for the development of the effect of the null field on CFF is the factor linking the two phenomena. The similarity of time periods does not necessarily establish the photoreceptor as a seat of the magnetic effect, and the actual causes for the magnetic phenomena may be located anywhere in the visual pathway from the photoreceptor to the visual cortex.

However, attributing the physiological observation to biochemical changes only does not fully explain the CFF effect. The biochemical changes are the result of the physical differences between the null field and the geomagnetic field. Magnetic constituents of the human body such as paramagnetic radicals of different organic molecules as well as nuclear magnetism of protons and other elements are responsive to the external field. In absence of the geomagnetic field dipolar magnetic moments "see" only the small local fields generated by their magnetic neighbors. Different coupling conditions between nuclear spins as well as between nuclear and electron spins are expected in the low magnetic field. Resonance conditions are also changed by the transition from the geomagnetic field to the very low field. Proton resonance is expected to be induced by a low frequency alternating field of a few cycles per second if the external field drops to a few gamma field strength. These are only some of the physical principles which may, via biochemical changes, alter the human capacity to follow the intermittent light changes in the CFF experiments.

Reports of the effects of null magnetic fields on living material by other authors offer at present limited information. Becker (14) observed a reduction in colony size and number in exposure of Staphylococcus aureus to one tenth of the geomagnetic field. Green and Halpern (15) exposed polyploid cells (human) and diploid cells (Chinese hamster, chicken embryo, human) to magnetic fields of 30 to 70 gamma and after short exposure periods observed no effect of such fields upon the cell cultures. Conley and associates (16) described a significant decrease in the acid phosphatase activity of serosal macrophages in mice exposed to a magnetic field of less than 80 gamma. Halpern and van Dyke (17) reported experiments with Swiss mice (Webster strain) which were exposed in mumetal cylinders for four months to well over a year to a magnetic field of about 50 gamma. The most pronounced effects were alopecia and premature death. Hair loss was due to plugging of the hair follicles by overgrowth of epithelial cells that showed distinct hyperplasia. Primary histopathological findings revealed a generalized diffuse hyperplasia in a number of organs which may have been the cause of death.

While in all previous observations on the biological effects of null magnetic fields, laboratory means have been used to generate the low field magnetic environment, such an environment has probably existed in the history of the Earth for prolonged periods of time. Since the beginning of this century the theory has been advanced that the geomagnetic field has changed its polarity repeatedly, with the last change taking place about 700,000 years ago (18). The behavior of the magnetic field during reversal is not yet known in detail, but it has been speculated that during reversal, the geomagnetic field decreases slowly in strength, passes through zero, and builds up again with a reversal of polarity. The zero field period is estimated to be in the range of thousands of years (19). It is well known that during certain periods of the Earth's history, some species of living organisms abruptly die out, while in other periods many new specimens suddenly appear. This observation was first connected to changes of the geomagnetic polarity by Harrison and Funnel (20) who noted that the extinction of several radiolarian species and the evidence of a geomagnetic polarity reversal occurred in the same bottom sediments of equatorial Pacific cores. Additional evidence of faunal changes during geomagnetic polarity reversals has since been accumulated (21). These catastrophic biological events during field reversal may represent a direct effect of the null magnetic field on the evolution of life on Earth. Uffen (22) hypothesized that in the absence of a geomagnetic field, cosmic radiation penetrates to the Earth's surface and increases the rate of genetic mutation. However, most of the cosmic radiation is absorbed in the atmosphere, and absence of the geomagnetic field does not increase surface radiation significantly. Thus, disappearance of Radiolaria during field reversals is more likely a direct effect of the zero field in which some function of the living material is disturbed.

The effects of the null magnetic field on CFF described in the present study seem to be part of a perplexing sequence of events which develop when some of the forces which have acted during the development of living matter are removed from the environment. The increased death rate of mice in Halpern and van Dyke's (17) experiments and the disappearance of the radiolarian assemblage (20) during a field reversal are cited as drastic examples of lack of adaptation. The CFF changes seem to be early specific reactions to the null magnetic field and should therefore be of special interest. Certain parallels can be drawn to the behavior of living beings in the gravity free state. In the gravity free and null magnetic field environments no immediate severe effects are observed, but certain functions which have developed in response to the environmental force fields obviously deteriorate in the null fields in a subtle way. In some species such functions may be vital to survival.

Presently available information suggests caution in prolonged human exposure to a magnetic field-free environment. Such an exposure should be preceded by lower primate experiments in which physiological and psychological reactions to the null field are carefully studied. A magnetic assessment of the extraterrestrial environment during space flight and at points of destination appears mandatory. The magnetic environment inside the Apollo capsule should be determined in an experimental null magnetic field, and local magnetic conditions of the landing sites on Moon and Mars should be known in advance of manned flight to these celestial bodies.

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13. ABSTRACT

The magnetosphere is an intrinsic component of the Earth environment, and travel beyond this sphere will expose man to near absence of a magnetic field. The present study is a continuation of a previous investigation of the physiological and psychological effects of prolonged exposure of man to low intensity magnetic fields. In support of previous findings, a significant gradual decrease of the scotopic flicker fusion threshold was observed from which the subjects recovered after exposure. Problems of life in a magnetic field-free environment are discussed.

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