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AEROMEDICAL REVIEWS

EFFECTS OF ACUTE RADIATION EXPOSURE ON HUMAN PERFORMANCE

Review 3-63

USAF SCHOOL OF AEROSPACE MEDICINE
AEROSPACE MEDICAL DIVISION (AFSC)
BROOKS AIR FORCE BASE, TEXAS

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A literal and parsimonious interpretation of the assigned topic would allow the speaker to fulfill his obligation quite honestly in approximately four seconds, or about as long as one might require to say, "There are no effects as far as we know." But this response would leave us far from satisfied, and it would create the false impression that the problem had been studied exhaustively throughout all the critical categories of behavior under various kinds, rates, and amounts of ionizing radiation. The distressing fact is, of course, that only two systematic human studies on this subject have been reported in the Western literature, and these can scarcely be said to provide a useful grasp of the total problem.

Under the circumstances, therefore, it has seemed appropriate to broaden the empirical base of this discussion by reference to studies of lower animals. As many of you know, the Radiobiology Laboratory at Austin, Tex., operated jointly by the USAF School of Aerospace Medicine and the University of Texas, has devoted a prominent share of its energies over the past ten years to systematic studies of radiation effects on the behavior of the *Macaca mulatta* monkey; and laboratories elsewhere have fed the burgeoning literature with behavioral studies of mice, rats, and dogs. Perhaps there are conditions and assumptions under which we should be willing to consider at least the infrahuman primate studies for whatever implications they may have for the behavior of man.

First, however, there is a sense of obligation to explain the rationale for the study of behavior in a radioactive environment. What can such studies tell us that we cannot learn merely by observing the impact of ionizing radiation on the cells, tissues, and organs of the body?

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WHY STUDY BEHAVIOR?

The principal reason for sending man into the aerospace environment is to take advantage of his abilities and skills as an equipment operator, a trouble-shooter and maintenance specialist, an observer and interpreter of dynamic situations, and a maker of decisions. Mercury flights have already shown the operational flexibility which can be realized by including man as a system component, and the operational plans for such systems as Gemini and Apollo have already been modified to take advantage of this versatility. In other words, man's capabilities are operationally important and without substitute, and we must therefore be concerned about their preservation.

Man's capabilities are joint functions of many determinants, including, but not limited to, the functional properties of biologic components and systems. Since biologic components and systems constitute the targets of ionizing radiation, one might be tempted to argue, as indeed many have argued, that their study would provide a sufficient basis for inferences about the fate of behavior. Unfortunately, even after nearly a century of serious effort on the part of many scientific disciplines, we have not yet acquired more than a few of the concrete details about the way in which somatic events participate in behavior, although perhaps we have learned a great deal about the explanatory sterility of certain viewpoints. One consequence of our continued ignorance of these matters is that we are unable to forecast changes in behavior from observed changes in somatic functions with sufficient accuracy to predict the operational impact of biologic damage, except, of course, under conditions of extreme insult. It is necessary, therefore, to observe and measure behavior directly in order to be able to say what is going to happen to it under specified exposure conditions. An ancillary product of such efforts may well turn out to be a better understanding of relationships between behavior and those events which occur inside the skin.

The foregoing premises have served as the foundation for modest but aggressive research efforts concentrated primarily at the USAF School of Aerospace Medicine. Such efforts have not been widespread among universities and other scientific institutions, for the resource requirements are formidable, and the monotonous occurrence of negative results soon blunts the enthusiasm of all but the most operationally minded investigators. Consequently, progress toward the achievement of a thoroughgoing research program has been slow. Many gaps are painfully evident, particularly with reference to dose dependency functions, relative behavioral effectiveness of different kinds of radiation, adequate coverage of the behavior spectrum, and the interactions of radiation effects with those of other stressors. Nevertheless a substantial amount of work has in fact been accomplished, and our review of it perhaps should start with the human studies.

HUMAN STUDIES

The Houston studies

Background. The two experimental human studies were initiated in 1951 at the M.D. Anderson Hospital and Tumor Clinic of Houston, Tex., for the purpose of charting the effects of low-level ionizing radiation on some of the psychomotor capabilities relevant to the operation of aircraft. The director and staff of the hospital had long been interested in the comparative value of radiotherapy and chemotherapy for the treatment of generalized neoplastic disease, and they foresaw no valid criticism of collateral studies of biologic and behavioral changes subsequent to the routine application of radiotherapy. All realized, of course, that ethical and moral considerations would necessitate compromises with some of the principles of experimental design. For example, medical considerations required that patients be assigned to treatment levels in accordance with professional judgment as to the severity of disease. Thus, the inability to employ random or stratified assignment methods virtually guaranteed some likelihood of confounding disease effects and treatment effects on the dependent variables. Further, language barriers, both of degree and kind, precluded the study of cognitive functions with available materials in which verbal comprehension occupied a central role. Despite such limitations, all agreed that the studies were feasible and desirable, and that negative results could be meaningfully interpreted and practically significant, even if the converse were not necessarily true.

Within the foregoing circumstances, two studies became possible throughout the next five years by virtue of close collaboration between the hospital and the USAF School of Aviation Medicine (Payne, 1959). The first study was concerned with the question whether a given air dose would have a greater effect when delivered in a single exposure than when delivered in a series of fractional exposures. The second study was organized as a straightforward dose-response study extending to relatively high exposure levels.

First study. The first study was organized about the therapeutic circumstance that certain patients were treated with whole-body doses delivered in single exposures, while others were given equivalent total exposures in five equal increments separated by intervals of 1 hour. Psychomotor performance data obtained from both types of patients made it possible to test the prediction that performance level would be an inverse function of total dose, more so with concentrated dosage than with temporally distributed dosage.

Subjects were male adults, usually in advanced stages of neoplastic disease not correctible by surgical intervention or localized radiation therapy. Ages ranged from 19 to 76 years.

Three well-known perceptual-motor tasks served as criteria of treatment effects. The USAF SAM Complex Coordination Test, shown in figure 1, required the subject to coordinate the movements of a stick and rudder bar in order to match successive positions of three red lights with three green lights. Score consisted of the number of matches accomplished within standardized trial periods. The USAF SAM Two-Hand Coordination Test, shown in figure 2, required the subject to operate two lathe-like crank handles in order to keep a cursor positioned on an eccentrically moving target. Score consisted of the amount of time the pointer was on the target during standardized trial periods. Finally, the USAF SAM Rotary Pursuit Test, shown in figure 3, required the subject to follow a rotating target with the tip of a stylus. Score consisted of time on target during standardized trial periods. Since these tests had been shown capable of accounting for a substantial portion of the variance of pilot training outcome, they were used successfully for the selection of aviation cadets during World

FIGURE 1

USAF SAM Complex Coordination Test.

War II. Thus the behaviors under observation were relevant to flying proficiency, although they were by no means predictive of its entire factorial structure.

Three exposure levels were available for study: 15, 25, and 50 r, as measured in air at the position of a plane which bisected the patient. Each level was reached either by a single exposure or by five equal fractional exposures separated by an interval of

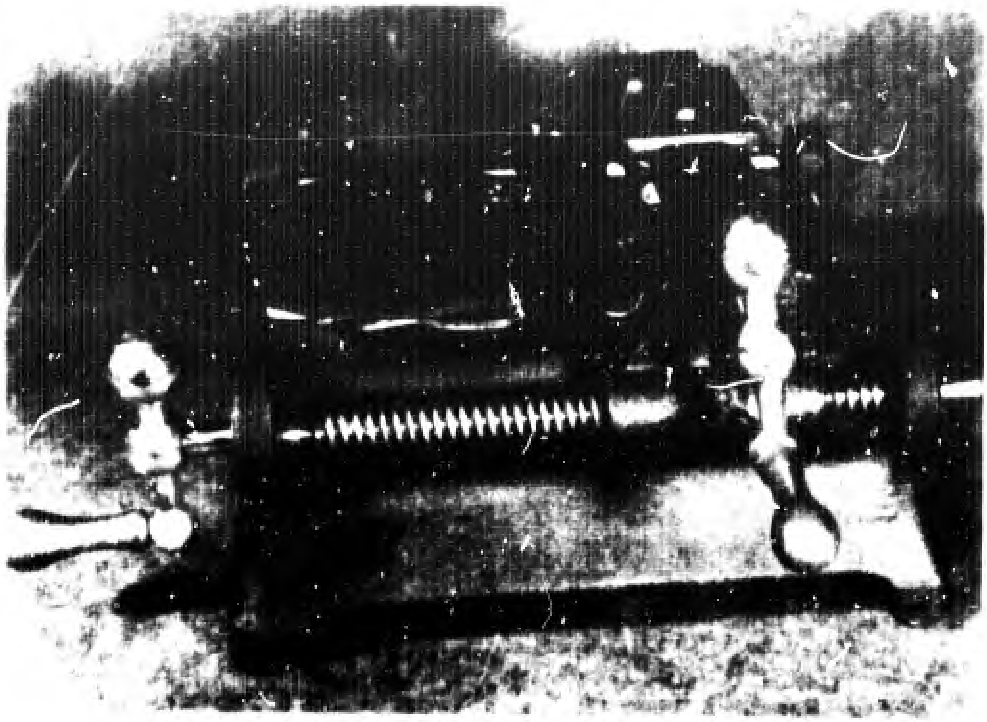

FIGURE 2

USAF SAM Two-Hand Coordination Test.

1 hour. Delivery was accomplished by a 400 kvp General Electric x-ray machine with Thoraeus III filtration having a half-value layer equivalent to 4.1 mm. of copper. At the target distance of 300 cm., the output was approximately 0.95 r min. One large field was used, the patient being treated in a lateral position with left and right sides alternated in proximity to the target. Air-wall ionization chambers (Farmer) were placed on the patient's skin during exposure in order to measure entrance and exit doses.

At about 0800 hours on the day of exposure, each subject was given formal test instructions and a standardized amount of preliminary practice on the three testing devices. Practice sessions were 2 minutes for the complex coordination and two-hand coordination tests, and 100 seconds (five 20-second trials separated

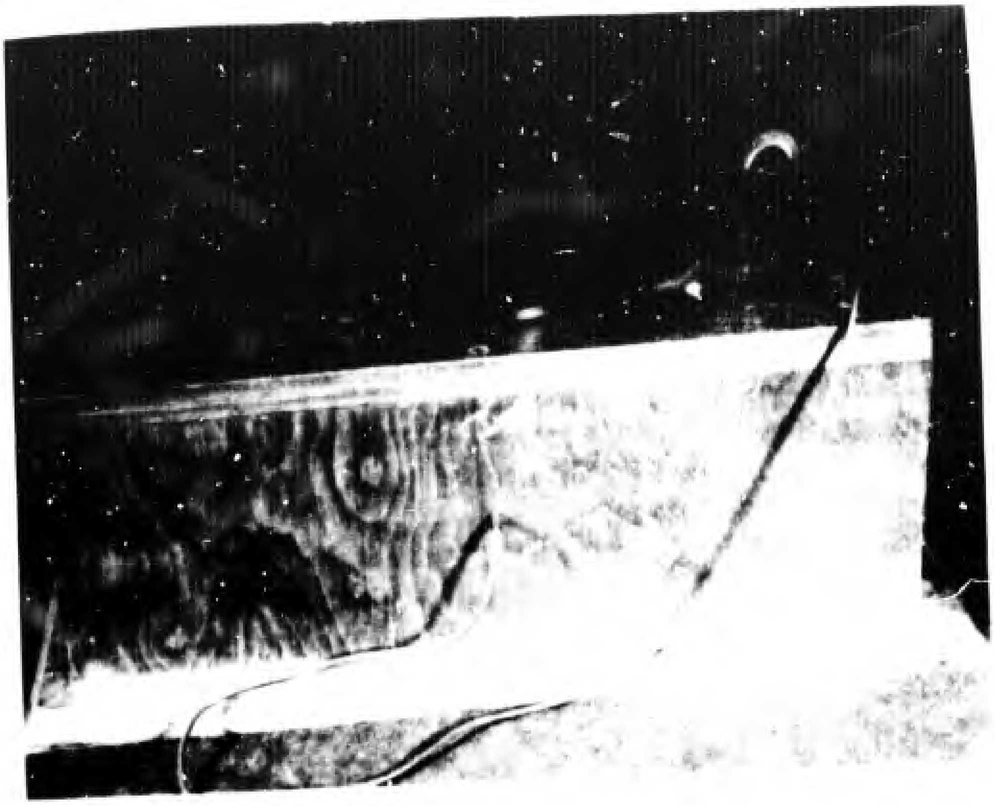

FIGURE 3

USAF SAM Rotary Pursuit Test.

by 10-second rests) for the rotary pursuit test. Following practice, the prescribed treatments were begun. One hour later the psychomotor testing sessions were resumed, and they were repeated thereafter at 2-hour intervals until six posttreatment sessions had been completed. Two testing sessions 8 hours apart were completed on the day following treatment. Additional testing was done on some of the subjects, but these data are not considered in the present study. Single-exposure subjects and multiple-exposure subjects within a given total exposure group were treated alike except that the latter were alternated between testing sessions and fractional treatment sessions until the five exposures had been accomplished.

Inasmuch as the performance under observation was measured early in the course of habit acquisition, two somewhat independent assessments of it were possible. The first was based simply on the total score achieved during the entire posttreatment testing sequence, while the second was an estimate of learning rate based upon the mean tangent of the angles defined by the abscissa of the performance curve and tangents drawn to successive equal segments of it. Both indexes were adjusted for multiple regression upon chronologic age and pretreatment performance levels before the final analysis of posttreatment variation was performed. This adjustment had the general effect of (1) reducing the contribution of these factors and factors correlated with them (such as type and severity of disease) to posttreatment variation, and (2) increasing the precision with which final tests of significance could be made. What remained for the final analysis was the variation attributable to the main experimental effects, their interaction, and residual differences between subjects.

Suffice it to say that only one of the six analyses (two criteria for each of three tests) provided even the slightest hint that performance was affected by the independent variables under consideration. An analysis of acquisition rate for the Rotary Pursuit Test, shown in table I, suggests that the effects of exposure level and method of delivery may have been correlated; that is, the effects of treatment levels may not have been the same at all exposure levels. A plot of subclass means, shown in figure 4,

TABLE I

Analysis of variance of acquisition rate scores for Rotary Pursuit Test

Source	d.f.	M. Sq.	F	P
Doses	2	6.1888	<1.00	
Methods	1	20.9941	2.05	.165
D x M	2	28.6785	2.79	.075
Error	70*	10.2589		
Total	75*			

*Reduced by 2 df for regression of posttreatment scores (y) upon pretreatment scores (x) and chronologic age (z).

$R_{y.xz} = .48$; $r_{xz} = -.16$; $r_{xy} = -.42$; $r_{zy} = .11$; $b_1 = .0048$; $b_2 = -.0900$.

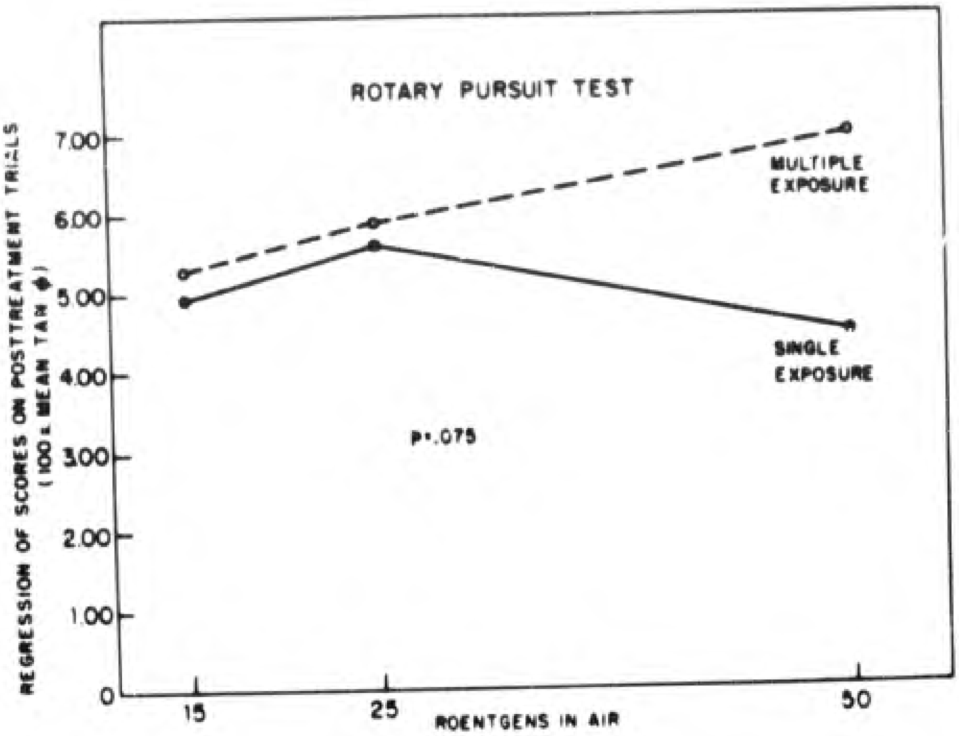

FIGURE 4

Rotary pursuit performance as a joint function of level and method of radiation exposure.

suggests that single exposures may have attenuated habit acquisition more than fractional exposures to the same levels, particularly at the highest level, in accordance with hypothesis. However, the probability levels associated with both *methods* and *interaction* effects are far from convincing, and the observed regressions of the two methods functions on the dosage variable are difficult to reconcile with the theoretic model.

Second study. Accumulated experience with therapeutic applications of whole-body radiation convinced the hospital staff of the wisdom of higher single doses than those which had been prescribed during the period covered by the first study. Consequently, it became possible to conduct psychomotor studies following single doses ranging from 0 to 200 r (in air) in steps of

25 r, and special arrangements for hospitalization permitted the observations to extend over a period of 10 days beyond treatment.

As before, subjects were adult males whose participation in the study was governed by their own consent and the judgment of the hospital staff. Ages ranged from 23 to 76 years. Testing devices were as previously described.

As before, patients were exposed in a lateral position with left and right sides alternated in proximity to the target. For approximately half the subjects, mostly those receiving below 75 r, the treatment was delivered as previously described. For the remainder, treatment was accomplished by a General Electric Maxitron operated at 250 kvp with a Thoraeus III filter providing half-value layer equivalent to about 3 mm. of copper. Output was about 3.8 r/min. Nine exposure levels, ranging from 0 through 200 r in 25-r steps, were sampled. Each subject received his prescribed exposure in a single session.

Beginning at approximately 0800 hours each day for 4 days prior to exposure, each subject was allowed a practice session on each testing device. Practice sessions both before and after exposure were 4 minutes for complex coordination and two-hand coordination, and 300 seconds (fifteen 20-second trials separated by 10-second rests) for rotary pursuit. Exposure occurred on the morning of the fifth day. One hour later the first posttreatment testing session was held, and this was repeated each day at approximately the same time for 9 days thereafter. All subjects, including controls, were treated essentially alike except for the amount of radiation to which they were exposed.

Analyses of variation in posttreatment achievement levels for complex coordination and two-hand coordination were based on the forty 1-minute performance samples obtained from each subject (10 days x 4 trials/day), while the analysis of rotary pursuit was based on the thirty 100-second performance samples from each subject (10 days x 3 trials/day). The scores of all subjects in each performance sample were adjusted for their multiple regression on chronologic age and pretreatment achievement levels, and

TABLE II

Analysis of variance of adjusted posttreatment achievement levels for rotary pursuit

Source	d.f.	M. Sq.	F	P
Groups (doses)	7	23,086	<1.00	ns
Ss treated alike	57	40,466		
Days	9	75,218	68.07	<.001
D x G	63	1,229	1.11	ns
Ss x D	513	1,105		
Trials/day	2	16,353	19.17	<.001
T x G	14	1,039	1.22	ns
Ss x T	114	853		
T x D	18	121	<1.00	
T x D x G	126	272	1.14	ns
Ss x T x D	1,026	238		
Total	1,949*			

*Reduced by 60 df for regression coefficients, as follows: Ss treated alike (−2), Ss x D (−18), Ss x T (−4), and Ss x T x D (−36).

the residual variation of the scores was then decomposed into main effects and interactions for determinations of statistical significance.

The outcomes for all testing devices are well represented by the analysis of rotary pursuit data, shown in table II. The highly significant variation associated with *days* and *trials/day,* when considered in conjunction with appropriate mean values, shows that significant amounts of learning occurred both within each day and from day to day. All radiation groups were essentially alike in this respect, as shown by the negligible interaction values, and there was no evidence of radiation impairment.

The data from each testing device were further analyzed in terms of the linear component of the habit acquisition curve, both within days and from day to day, but none of the analyses implicated radiation exposure as a significant source of variation.

TABLE III

Analysis of variance of quadratic component of scores by days for complex coordination

Source	d.f.	M. Sq.	F	P
Between radiation groups	8	.0028206	3.33	<.01
Within groups	58	.00084699		
Total	66			

Comparable analyses were made in terms of the quadratic component of the acquisition curve. The results were negative for two-hand coordination and rotary pursuit, but those for complex coordination were significant, as shown in table III. A plot of the mean coefficients against exposure values, shown in figure 5, suggests that the quadratic component of the 10-day performance curve became more negative, the more intense the radiation exposure. In other words, the more intense the exposure, the more likely it was that performance was falling, rather than rising, toward the end of the 10-day period of measurement.

Except for the curvature aspect of the 10-day performance sequence for complex coordination, one can summarize these two studies by saying that there is no dependable evidence that exposure to ionizing radiation affected the variables measured. Whether this exception is a true radiation effect is debatable. It could just as well have been a disease effect, for we must presume that the prescribed exposure intensity bore some relationship to the true severity of the disease. Whatever its source, the effect probably represents progressive motor weakness or fatigue in the operation of the spring-loaded controls rather than decrements in the cognitive aspects of the task. Finally, it seems important to re-emphasize that the application of these results to operational problems should be made with cautious regard for the medical status of the subjects and the limited relevance of experimental criteria.

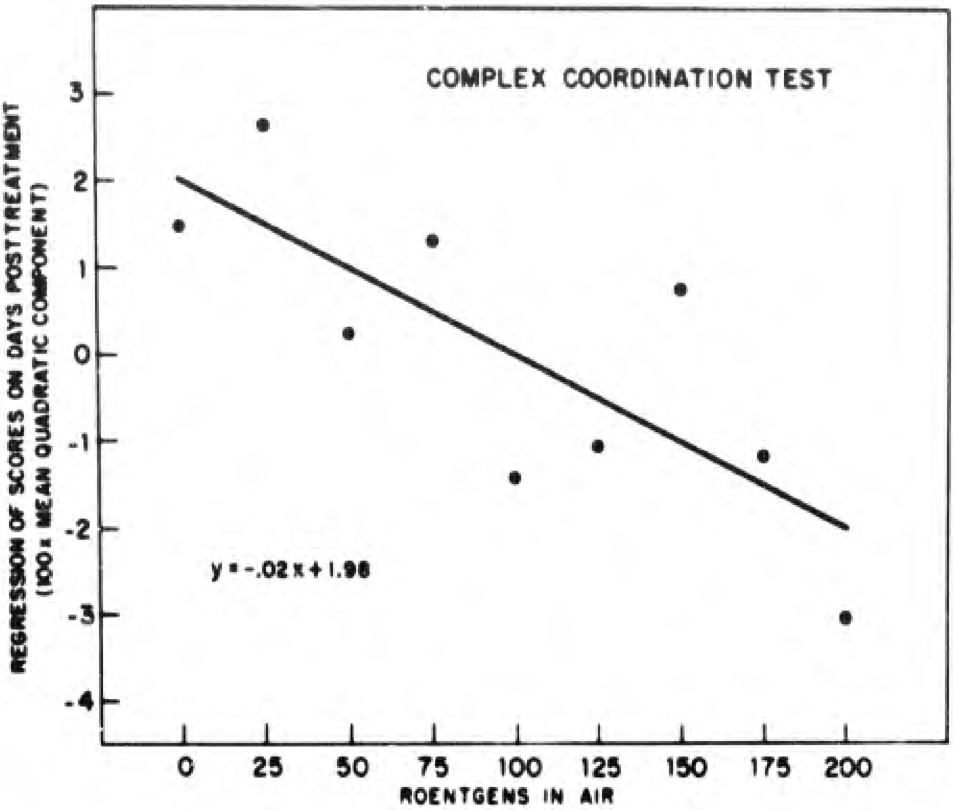

FIGURE 5

Quadratic component of complex coordination learning curve as a function of radiation exposure level.

Clinical observations

Although lacking the precision of systematic experimental studies, certain observations acquired through clinical studies of bomb casualties, accidental exposures, and therapeutic experiences deserve careful consideration because of their attention to what Furchtgott (1956) has called "behaviorally significant effects." For example, Keller (1946) noted fatigability as an almost universal complaint in his study of bomb casualties; and Gerstner (1957, 1958) commented on the appearance of listlessness, apathy, headache, and drowsiness "within a few hours" of exposure to radiotherapy. Miller, Fletcher, and Gerstner (1957) found about 50 percent of their patients showing fatigue, anorexia, and nausea shortly after radiotherapeutic exposures ranging from 125 to 175 r. Further studies of therapeutic experience by Levin, Schneider, and Gerstner (1959) observed that whole-body exposures of 150 to 200 r left patients asymptomatic for about an hour, but thereafter precipitated feelings of fatigue, apathy, dizziness, and headache, and produced appearances of depression and energy depletion. Thoma and Wald (1959) reported similar findings in their review of accidental exposures. Finally, Furchtgott (1952) reported studies, unavailable to him in original form, which suggested that radiation of the skin in "suberythemal doses" increased scotopic thresholds for several days and produced decrements in dark adaptation levels.

One, of course, cannot foresee with confidence what impact these effects might have on task performance, since high levels of training and motivation often sustain an operator to outstanding levels of achievement despite his infirmities. On the other hand, we can all agree that such effects represent potential liabilities that operators would be better off without.

The British study

The sparse account of human studies would not be complete without reference to a recent paper by Frisby (1961). A British physician discovered one day that he had acquired a carcinoma of the tongue. As radiation therapy progressed, he came vaguely to feel that certain behavioral changes were taking place, and finally, after four weeks of this, he offered a psychologist an opportunity to study certain intellectual and perceptual functions by psychometric methods. Tests involving choice reaction time, cancellation, and fractions were administered twice daily (except Saturday and Sunday), sometimes by the psychologist and sometimes by the secretary, until a total of 6,870 r had been delivered to the lesion, 5,000 r to a nearby gland, and 7,530 r to the skin. There was no evidence of radiation effect.

INFRAHUMAN PRIMATE STUDIES

The scarcity of human data may be regarded as compensated in part by a wide assortment of studies conducted on the infrahuman primate, particularly on the *M. mulatta.* Whether such studies are truly useful depends, of course, on the validity of assumptions one makes about the phylogenetic continuity of behavioral processes. There are some who insist that there is a fundamental discontinuity between the behaviors of man and lower animals, and that little or nothing can be safely inferred about one from studies of the other. On the other hand, one should remember that such assertions are usually treated as hypotheses by those who study subhuman behavior, and the acceptance of the doctrine before the fact would therefore seem to beg the question. Scholars in this field generally take the position that the study of lower animals promotes the understanding of human behavior to the degree that fundamental principles anticipate and embrace both sets of facts, an event which occurs more conclusively than most people today realize. From a clinical point of view it is interesting to note the conclusion drawn by Zellmer and Pickering (1960) that the *M. mulatta* demonstrates all the important aspects of the acute radiation syndrome. Diagnostic and prognostic signs (diarrhea, vomiting, purpura, anorexia, epilation, etc.) occur about as frequently and with about the same latency as in humans, and the three modes of radiation death (CNS, gastrointestinal, and hematopoietic) are about as well illustrated. Thus there is a very substantial amount of conviction that the *M. mulatta* is an exceptionally suitable substitute for the human as an experimental animal. Fortunately so, for the study of lower primates permits the observation of omplicated processes in their more elementary forms, and it mits the deliberate arrangement and control of a great variety nditions for the satisfaction of experimental objectives.

avioral methodology

The broad assortment of devices and technics commonly used to study the animal's intellectual, perceptual, and motor capabilities are described in any textbook of comparative psychology (e.g., Stone, 1951), as well as in the cited references, and any attempt to review them here would impose needlessly upon time and patience. In general, however, it may facilitate understanding to note that the investigator's ability to observe and measure these processes entails two fundamental requirements. First he must devise a problem the solution of which embodies the specified characteristics of such processes and falls within the anatomic and physiologic capabilities of the organism. Second, he must provide an incentive which renders the solution worth the animal's effort. The rigor and precision with which he can study the processes depends, in part, upon the extent to which he can (a) control the environmental conditions and (b) quantify the responses in terms of their appropriateness, vigor, frequency, and latency.

The major categories of behavior which have served as focal points of research on the radiated monkey are (a) the learning and retention of discrimination habits, (b) the generalization of habits to novel situations, (c) the manipulation of environmental objects, (d) the delay of response to cues no longer present, (e) the breadth of attention to peripheral cues, (f) the solution of puzzles, (g) locomotion, and (h) free cage behavior in a comparatively unstructured environment. These categories merely represent convenient ways of classifying various aspects of the interaction between organism and environment, and one should understand that they are rigorously definable in terms of specific experimental operations.

Radiation effects

Learning and retention. Early systematic efforts explored the success with which the animal could reproduce discriminations which had been mastered prior to exposure. For example, Kaplan and Gentry (1954) trained animals on a serial discrimination task composed of 15 pairs of stereometric objects, then exposed them to 1,000 r of whole-body radiation delivered at 15 r/min. Response evocation was rare on early postexposure trials, but significant retention was demonstrated from 8 hours postexposure until [illegible] hours before death. Kaplan et al. (1954) repeated the foregoing [illegible] with minor variations in which testing was resumed 24 hours [illegible]posure and continued twice daily until the animals could [illegible]ger enter the transport cages. Although the radiated animals performed somewhat less well than controls after the third day, they exhibited significant degrees of retention virtually up to the point of collapse. Melching and Kaplan (1954) modified the procedure by requiring animals to discriminate objects in order to select an alley in which they could avoid electrical shock. Tests of retention conducted between 2 and 10 hours following the delivery of 1,500 r at 34 r/min. were essentially negative. Rogers et al. (1954) reported comparable results after exposures to 1,295 r. Kaplan et al. (1960), analyzing discrimination ability following massive doses of gamma radiation ranging from 1,000 to 30,000 r at 1,000 r/min., concluded that some animals were able to accept up to 5,000 r without performing poorly, provided they were physically able to perform at all.

Harlow and Moon (1956) trained animals on a variety of tasks, including planometric discrimination and oddity problems, then exposed half of them to 100 r every 35 days until death. Formal testing was discontinued after the ninth exposure period for lack of survivors, but there was no evidence prior to death that radiation had degraded the ability to solve even the most complex learning problems, and animals on the verge of death maintained high performance levels until they were so weak that overt response was no longer possible. Similarly, Riopelle, Grodsky, and Ades (1956) examined the effects of cumulative exposures adding to 2,000 r on object quality discrimination only to find that the performance of radiated animals was equal to *or better than* that of controls.

When it became evident that the retention of simple discrimination habits was not seriously affected even by massive doses of radiation, efforts were made to devise more complicated problems and to examine the acquisition process, as opposed to the retention process, at generally lower levels of exposure. For example, eight months postexposure to average doses up to 550 rem, Warren, Kaplan, and Greenwood (1955) trained animals to respond correctly to each of 108 pairs of multidimensional objects, then reversed the reinforcing operation so that the opposite member of each pair became the symbol of reward. Prereversal performance was not affected by the dosage levels; and postreversal performance, although somewhat deficient, was not correlated with dose. McDowell and Brown (1959a) varied the cue reversal technic by rewarding the oddly colored of three objects during prereversal training, then rewarding the oddly shaped of the three objects during postreversal training. Radiation exposure up to approximately 600 rem average dose failed to affect either phase of training in terms of errors committed. McDowell, Brown, and White (1961) used a comparable technic to assess the impact of massive focal radiation to the head, but with negative results.

Overall and Brown (1959) found no radiation effects when the task was one of learning to respond to the most recently rewarded position. Later, however, Overall, Brown, and Gentry (1960) showed that the ability to learn size relationships between objects declined as a linear function of dosages which had been delivered three years prior to test (0 to 616 rep mixed neutron and gamma). Brown, Overall, and Blodgett (1959) presented consecutive discrimination problems in which both positive and negative cues in earlier series were selected at random to become negative when paired with new stimuli. Mixed neutron and gamma radiation up to 616 rep had no effect on the solution of this problem.

McDowell and Brown (1960b) adapted the Landoldt Ring principle to a series of eight problems ranging in difficulty from a 90° break to a 1° break in order to study the visual acuity of animals which had been exposed to as much as 616 rep three years earlier. All animals learned the easier problems readily, but they failed the more difficult ones in accordance with dosage received. Roughly comparable results were obtained following massive focal radiation to the head (McDowell and Brown, 1960b). However, neither set of results seemed decisive with respect to whether the deficit was a matter of visual acuity per se or planometric discrimination learning. The authors argued the former interpretation on the grounds that the easier problems were in fact learned.

Generalization of habits. The ability to transfer principles acquired through experience with one set of problems to the solution of a new set of problems is generally regarded as a very high order of intellectual achievement. Such processes are studied in lower animals by presenting the training problem in such a way that reinforcement is applied to all objects which have some particular feature in common, say triangularity, while nonreinforcement is applied to those objects which lack the feature. The critical test of transfer involves additional problems which incorporate some variant of the differentiated cue. Kaplan and Gentry (1953) explored the effects of radiation on this ability by comparing controls with animals that had received whole-body exposure to 400 r at about 16 r/min. Half the exposed animals had their heads and spinal cords shielded. Transfer tests applied immediately postexposure as well as several months later gave no evidence of a deleterious effect. Comparable results were found with animals which had been exposed to whole-body doses as high as 616 rep (McDowell, 1960), and to focal head doses as high as 3,000 r (McDowell and Brown, 1959c).

Manipulation. Leary and Ruch (1955) noted some decline in the ability to pull weights and manipulate mechanical puzzles shortly after the delivery of 200 r or more, but these effects appeared to be transient. On the other hand, Davis, McDowell, and Deter (1956) observed no important changes in manipulation ability after as much as 400 r.

Delayed response. The measurement of an animal's ability to postpone its response to some reward or to some sign of reward following concealment from view was one of the earliest behavioristic approaches to the study of mental processes in lower animals. This process assumed considerable theoretic significance because of the implication that the animal, no longer able to sense the object, was responding to some internalized representation of it, thereby exhibiting implicit behavior remarkably like that found at the human level. Also, the amount of delay attainable was generally correlated with phylogenetic sequence, ranging from about 10 seconds in the rat to much longer in the human. Davis, McDowell, and Deter (1956) were unable to degrade this response with acute whole-body exposures up to 400 r, and later studies involving up to about 1,100 rem average dose found experimental animals performing about as well as (Davis, Elam, and McDowell, 1958) or better than (McDowell and Brown, 1958b) controls. Multiple exposures eventuating in total doses of 2,000 r (Riopelle, 1959; Riopelle, Grodsky, and Ades, 1956) were likewise without effect, as were doses of 100 r given every 35 days until death (Harlow and Moon, 1956). McDowell, Brown, and White (1961) found no significant effect two years after their animals' heads had been exposed to 6,000 r in two increments of 3,000 r spaced 30 days apart. Harlow, Schiltz, and Settlage (1955) were able to degrade the response temporarily with 8,000 r delivered to the head, but recovery was detectable 4 days later and was complete on the eighth day.

An unusual study worthy of note attempted to assess the impact of low-energy heavy nuclear components of primary cosmic radiation by exposing two Java monkeys to altitudes of 90,000 to 95,000 feet for 62 hours (Harlow, Schrier, and Simons, 1956). Delayed response, as well as other processes, was unaffected by this exposure, but the absence of track plate data precluded a determination of exposure level. About all one can say is that the animals were exposed to a hostile environment, and if they were hit, they were not measurably affected.

Attentiveness to environmental cues. Riopelle, Grodsky, and Ades (1956) were perhaps the first to suggest that the often superior performance of radiated animals represents a kind of tranquilizing effect in which the animal is rendered less responsive to peripheral stimuli and consequently more attentive to the cues relevant to the problem presented for solution. Subsequent investigators confirmed this facilitative effect on oddity reversal problems (McDowell and Brown, 1959a), delayed response problems (McDowell and Brown, 1958b), discrimination problems (McDowell and Brown, 1958a; McDowell, Brown, and Wicker, 1959), and easier levels of the Landoldt Ring problem (Brown and McDowell, 1960). Further studies left no doubt that radiation narrowed the animal's scope of attention (McDowell, 1958; Overall and Brown, 1958; Brown, Carr, and Overall, 1958), producing as it were, a kind of "reduction in life space" (Davis, Elam, and McDowell, 1958). Although one might be tempted at first to rejoice over what might appear to be an unexpected bonus from an otherwise hostile environment, a more sober and insightful reflection on the reasons for these facilitative effects marks them as unwanted phenomena worthy of serious concern.

Miscellaneous effects. Leary (1955) observed changes in the food preferences of animals which had been exposed to as little as 50 r, and Davis (1958) noted the persistence of such changes through at least 14 months postexposure. Several studies of free cage behavior have identified lower aggression (McDowell, Davis, and Steele, 1956) and exaggerated self-care (McDowell and Brown, 1958c, d) as consequences of whole-body doses as low as 400 r. At least one study has suggested an increase in reaction time as a function of dosage ranging from 0 to 670 rem (McDowell, Brown, and Wicker, 1961).

SUMMARY

More than fifty studies of anthropoid behavior observed under various kinds, rates, and amounts of ionizing radiation have shown, on balance, that behavioral functions are highly resistant to acute whole-body doses well above those required to produce troublesome manifestations of acute radiation sickness. Despite this overwhelming evidence of resistance, however, several aspects of behavior are clearly not impregnable. Further effort, therefore, is required to relate such aspects both to the physical dimensions of the radiation environment and the visible damage produced in biologic tissues, with particular emphasis on the modifying properties of other stressors.

From a practical and conservative point of view, any exposure intense enough to embarrass an individual's normal physiologic mode should be regarded as behaviorally significant because it imposes constraints upon the convenience with which the individual can adapt to environmental circumstances. In terms of immediate effects, present knowledge suggests the acute radiation syndrome as the ruling factor in the specification of permissible acute exposure levels.

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