Accid. Anal. & Prev. Vol. 17, No. 4, pp. 323–345, 1985
Printed in the U.S.A.

0001–4575/85 $3.00 + .00

MARIHUANA AND DRIVING

HERBERT MOSKOWITZ
University of California at Los Angeles, Los Angeles, CA 90024, U.S.A.

Abstract—A review was performed of the marihuana and driving literature, both epidemiological and experimental. It was noted that epidemiological studies face considerable difficulties in obtaining estimates of risks involved for drivers utilizing marihuana due to the rapid decline in blood levels of tetrahydrocannabinol. On the other hand, experimental studies examining the relationship between administered marihuana dose and performance have identified many driving-related areas as exhibiting impairment. Areas impaired include coordination, tracking, perception, vigilance and performance in both driving simulators and on the road. Other behavioral areas of lesser importance for driving also exhibited evidence of impairment by marihuana. Areas for further research are suggested.

INTRODUCTION

Public concern with marihuana has primarily focused on chronic effects, those resulting after an extended use. Increasing attention is now focused on the behavioral effects of the acute use of marihuana, which have to be evaluated as extensively as the effects on cardiovascular, respiration, reproduction and genetic systems. It should be noted that another intoxicating drug, alcohol, causes more accident deaths yearly than are produced by chronic abuse or alcoholism.

Recent studies have examined the acute behavioral impairment produced by psychotropic drugs (both illegal such as marihuana, cocaine and legal prescription drugs such as tranquilizers, hypnotics, etc.) to determine whether their use is associated with skills performance decrements. These, in turn, lead to increased accident probability in such man–machine interactions as driving, recreation, flying and control of complex machinery.

In this paper we shall examine what is known about the behavioral effects of the most frequently used illicit psychotropic drug, marihuana. Our initial discussion will consider the information derived from epidemiological studies—statistical studies examining the frequency of accidents in individuals who have consumed drugs. Most of our discussion will be on experimental studies in which known dosages of marihuana were given subjects and their performances measured on behavioral tests.

EPIDEMIOLOGICAL STUDIES OF MARIHUANA AND DRIVING ACCIDENTS

Decades of epidemiological research on the relationship between blood alcohol concentration (BAC) and the probability of accident involvement has created a paradigm for marihuana researchers. In studies of alcohol accident involvement (such as by Borkenstein *et al.* [1964]), investigators rushed to the scene of accidents and obtained breath samples from the drivers involved. The BACs derived from these breath samples were then compared with BACs derived from breath samples of randomly selected drivers passing the accident site in the same direction at the same time of day and day of week. These studies control for such variables as time of day, nature of road, direction of travel, weather conditions, etc. These highly successful studies have been predicated upon two assumptions. The first is that nearly all accident drivers, as well as drivers requested to volunteer from the population at risk, will cooperate in supplying a breath sample. And this, in fact, occurs. Roughly 97% cooperation is typical of such roadside surveys. While there is subsidiary information to suggest that those who refuse to participate are more likely to have alcohol present in their body, the overwhelming participation renders the few percent of nonparticipation no impediment to reliable conclusions.

A second basic assumption is that the blood alcohol concentration estimate obtained from these breath samples will be highly correlated with the degree of impairment. This assumption is well substantiated by the experimental literature. Although factors such as history of drinking, experience as a driver, among others, have been shown to modulate the relationship between blood alcohol concentration and degree of impairment, the fundamental correlation remains high. Moreover, the rate of change of blood alcohol concentration over time is relatively slow

(being on average .017% BAC per hour), so that samples obtained from drivers within an hour or longer can either be accepted as such or extrapolated back to obtain an accurate estimate of the BAC at the time of accident.

Unfortunately, these assumptions do not hold well for investigations into the relationship between tetrahydrocannabinol (THC) blood concentration and accident probabilities. Due to the necessity of sampling blood rather than breath, only 50–75% of drivers solicited agree to participate. Thus, even if a 100% sample from the accident involved drivers could be obtained, the necessary control comparison group would be missing. Moreover, the accident involved drivers typically are no more cooperative. Most studies dealing with the issue of the relationship between marihuana use and accident probability have resorted to obtaining blood samples from fatally injured drivers through the cooperation of coroners. But lacking a proper control group from the population at risk, interpretation of these studies are difficult.

The second major difficulty is that variations in THC blood concentration within an individual and variations in degree of impairment are not highly correlated. The problem can be illustrated by data from a recent study of McBay and Owens [1981] which included a figure of the mean and range of blood THC values in 5 subjects who smoked a marihuana cigarette containing 9 mg of delta-9 THC. Smoking took between 7 and 13 minutes. The peak blood THC concentration occurred midway during the smoking period. At 20 minutes after the start of smoking, or roughly 10 minutes after cessation, the blood THC concentration had dropped to one-third of the peak value. At 60-minutes postsmoking, the average value was one-eighth of the peak value, and by 120 minutes after initiation of smoking had dropped to a mean of 3 mcg per liter, the cutoff point utilized by the authors for a positive response. In contrast, as illustrated by Moskowitz and Sharma [1979], single doses of marihuana can produce significant detrimental effects for more than 8 hours. Typically, peak effects on psychomotor impairment occur 1-hour postsmoking. Because of the lack of correlation between an individual's blood THC concentration and degree of impairment, a negative finding for blood THC in an accident victim does not preclude the possibility that marihuana was involved in producing that accident. Further, the decline in THC blood concentration places extraordinary demands on accident investigators to arrive at the scene of an accident and obtain blood samples rapidly.

In the McBay and Owens study [1981] of single car accident fatalities, the authors accepted specimens from individuals who had died within 1 hour of the accident. This raises difficulties in evaluating the number of negative findings of THC for the accident victim.

Before continuing the discussion of accident investigations, it should be noted that three other methodologies have been used to obtain information on the relationship between marihuana use and dangers in driving. These are: (a) marihuana presence in drivers arrested for impaired driving, (b) questionnaires requesting information from populations likely to contain marihuana users and (c) studying the driving records of known marihuana users. All of these methods present considerable difficulties in interpreting their results.

A widely reported study in California [Reeve, 1979] obtained blood samples from 1972 drivers arrested for impaired driving. These samples were examined for THC presence using a radioimmunoassay technique. Sixteen percent contained THC. Interpretation of this is, however, extremely difficult. In California, when arrested for impaired driving, a driver has a choice of offering a breath, blood or urine sample. Roughly 40% of the drivers submit a blood sample. However, the percentage of drivers offering blood samples varies considerably among law enforcement districts and is apparently subject to pressures from officers. The study contained no information permitting a comparison of the characteristics of drivers who supplied blood and those who submitted breath or urine samples. Moreover, it is not clear that the utilized blood samples were a random selection from the larger pool of blood samples of all drivers who gave blood samples. Among difficulties in accepting that conclusion is the finding that the percentage of drivers with positive blood THCs is roughly independent of age. This flies in the face of extensive evidence that marihuana use is highly concentrated among young males. While this research technique might theoretically be employed to supply information, no successful examples are available.

Smart [1974] and Waller *et al.* [1974] have utilized self-reporting questionnaires to examine the relationship between marihuana use and driving accidents. These studies can contribute information regarding marihuana use frequency, but have limited ability to suggest whether a

relationship exists between marihuana use and accident probability. Assuming complete honesty by the questionnaire respondent, it nevertheless requires a subjective introspective evaluation by the driver as to whether he was under the influence of marihuana at the time of the accident. Laboratory studies have frequently found impairment for hours beyond the disappearance of a subjective "high." Self-reporting questionnaire studies do demonstrate that many individuals smoke marihuana and drive shortly thereafter.

Crancer and Quiring [1968] attempted to approach the problem of marihuana use in driving accidents by examining the driving records of known drug users. These studies have several inherent problems. The probability of being labeled as a known drug user is not randomly distributed in the population of drug users. It is likely to be associated with many socioeconomic, racial and cultural factors, age and sex variables, which are themselves differentially correlated with the probability of accident occurrence. It, thus, becomes impossible to extricate the influence of marihuana or other drug use from other characteristics of users which play roles in accident probability.

Clearly, investigating the relationship between the presence of marihuana in the body and accident probability requires avoidance of subjective report techniques. But as noted above, more objective blood sampling techniques are also fraught with difficulties.

Nichols [1971] reviewed pre-1970 studies of drug involvement in accidents, primarily fatal crashes. These will not be rediscussed since the sensitivity and reliability of chemical analytical techniques for marihuana at that time were inadequate. Further, there will be no discussion here of recent attempts to obtain information about THC body content utilizing techniques of swabbing the face, lips, hands, etc., since the reliability of this technique is not yet established. Rather, the discussion will be restricted to three recent studies which have taken blood samples; Teale *et al.* [1977], McBay and Owens [1981] and Cimbura [1980].

The Teale *et al.* [1977] study examined 66 blood specimens, all but one obtained by soliciting English and Welsh coroners for samples from fatally injured drivers. The victims included 54 car drivers and 12 motorcyclists, with one sample specifically sent because the motorcyclist was suspected of marihuana use. The time relationship between the accident and the death of the drivers was not specified. The age distribution of the samples was not representative of dead drivers in general. The authors speculated that the specimens submitted came from pathologists who suspected that marihuana might have been involved. In any case, radioimmunoassay found 6 of the 66 fatal drivers used marihuana.

A study by McBay and Owens [1981] used specimens from 100 North Carolina vehicle operators in single vehicle crashes who died within 1 hour of the accident. While the radioimmunoassay technique used for analysis had greater sensitivity, apparently for reliability reasons, no specimen which contained less than 3 micrograms THC per liter blood was reported positive. THC was present in the blood of 9 of the 100 operators. In 6 of the 9 cases, alcohol levels beyond the legal limit were also found. Since no information is available on the presence of marihuana in the at-risk population at these accident sites, it is hard to determine whether the presence of marihuana in these 100 cases indicates an overrepresentation in accidents.

Perhaps the most sophisticated examination of marihuana presence in accident victims was performed by Cimbura *et al.* [1980]. This study examined body specimens from drivers and pedestrians fatally injured in the Canadian Province of Ontario, between April 1978 and March 1979. Criteria for inclusion in the study included a minimum age of 14 years, death within one hour after arrival at the hospital, and that both blood and urine samples be available. Of the 1031 fatally injured drivers and pedestrians during the study period, 484 or 47% met all the criteria for inclusion. It should be noted that 77% of the original sample were dead after impact or by arrival at the hospital, and only 7% died within the first hour following hospital arrival.

The authors discuss the characteristics of the final sample of victims to evaluate whether they were representative of all the fatally injured drivers and pedestrians, or if any of the exclusion criteria led to a bias in selection. Their conclusions are that the characteristics of the 484 victims used in the study were selected from the 1031 initial victims by criteria that did not substantially alter the characteristics of the sample population from that of the initial group of victims.

Two chemical analytic procedures were used to determine the presence of cannabinoids

in the urine and THC in the blood. The urine test for cannabinoids would reveal whether the individual had used marihuana within the preceding several days. The blood test for THC would reliably indicate whether the subject had utilized marihuana within 1 to 3 hours of death. Twelve percent of the victims had positive urine tests for cannabinoids, of which 3% were also positive for THC in the blood. The victims using marihuana were typically young (mean age of 22) and 97% male. The overwhelming majority of marihuana users had also consumed large quantities of alcohol.

It is not easy to interpret this data, since no comparable control group was sampled to determine the incidence of cannabinoids in the urine and THC in the blood in the at-risk population in this situation. In a subsequent publication by Warren and Simpson [1980], an attempt was made to compare this data with information derived from questionnaire responses obtained during roadside surveys in the Province of Alberta, during 1974. Three percent of those stopped reported recent marihuana use. However, as the authors recognized, this must remain a very weak comparison, given the differences in geographic location, time and methodology. More importantly, the duration of influence of marihuana on behavior is more extensive than either the blood THC test or subjective evaluation is likely to reveal. That 12% of the victims had utilized marihuana within the preceding several days does seem likely to be an overrepresentation.

In an attempt to circumvent some of the difficulties involved in these epidemiological studies which have difficulty in obtaining control groups, Warren *et al.* [1980] reanalyzed the data from Cimbura *et al.* [1980]. They utilized an induced exposure methodology which develops an index of culpability. Culpability indexes the extent to which drug-using drivers are assigned responsibility for causing a collision in comparison to individuals from the same sample who have also caused an accident but who consumed neither alcohol nor any other drug. Individuals with no alcohol or drugs had a culpability index by definition of 1.0. Individuals with salicylate were found to also have a culpability index of 1.0. This is of some significance because it serves as an internal check on the technique, agreeing with a prior assumption that it would be unlikely for aspirin users to be overrepresented in accidents. However, victims with cannabinoids present in the urine were found to have a culpability index of 1.7, the same culpability level found for alcohol.

The presence of antihistamines produced a culpability index of 1.5 and tranquilizers/antidepressants 1.8. Given the problems in executing epidemiological studies where it is so difficult to obtain adequate control groups, it would appear that the Cimbura [1980] study and its subsequent analysis present the best epidemiological evidence that the presence of marihuana is likely to increase the probability of producing an accident.

In conclusion, given the problems of the low correlation between THC blood level and behavioral impairment for marihuana and the difficulty of obtaining adequate control samples for the population at risk in accidents, the degree of information which can be brought to bear by epidemiological studies on whether marihuana use produces an increase in accidents is limited. It is of interest that the most sophisticated such study yet performed does indicate that marihuana use is associated with increased accident probability. However, the limitations of the epidemiological technique in contributing information to this issue places prime emphasis on experimental studies as a means of investigating the effects of marihuana upon traffic safety.

Coordination

The LaGuardia report [Mayor's Committee on Marihuana, 1944] examined the effect of "moderate" and "high" doses of orally ingested marihuana on body sway as measured by a series of pulleys attached to the head of the subject, hand steadiness as measured by inserting a needle-like stylus into a small hole in a metal disc, speed of tapping, and strength of hand grip as measured by a dynamometer. Both hand unsteadiness and body sway were increased greatly by both marihuana treatments. Speed of tapping was only slightly affected by the large dose and not by the smaller dose. The peak effect was not reached until the fourth hour after administration of the oral dose and impairment continued until the eighth hour.

Clark *et al.* [1970] examined hand steadiness using an apparatus similar to the above. Eighteen subjects were administered .3 mg/kg B.W. of delta-9 THC in an oral treatment. Both

the number of contacts of the stylus with the edge of the hole and the contact time were significantly increased by marihuana.

Kiplinger, *et al.* [1971] examined 15 subjects, 8 with prior marihuana experience and 7 naive. Dosages were 0, 6.25, 12.5, 25 and 50 mcg/kg B.W. of delta-9 THC. However, these dosages should be multiplied by two for comparison with other studies, since the authors were apparently indicating delivered dosages based on their estimate that 50% of the THC in a cigarette actually is delivered in the smoke. The study examined a version of body sway described as stability of stance, with subjects standing on a wobble board. Subjects were tested under four conditions; once with eyes open, once with eyes closed, once with eyes open and a vibrator attached to the wobble board, and once with eyes closed and the vibrator on. There was a dose-related increase in impairment of stability on all four measures, with increased sway occurring with eyes closed and with the vibrator on. The slopes of the dose response curves for the four experimental conditions were similar.

Evans *et al.* [1973] examined body sway on a wobble board after smoked administration of low levels of delta-9 THC, namely, 0, 3, 6 and 9 mcg/kg B.W. Again, this assumed delivered doses; the actual administered doses were twice these. The test was performed with eyes open. Significant impairment was found for these very low dosages.

Rafaelsen *et al.* [1973] examined subjects on a finger labyrinth constructed of cardboard plates and thin wooden sticks. The subjects were blindfolded and had to move their fingers through the maze as rapidly as possible. Eight subjects received oral marihuana doses of 8, 12 and 16 mg delta-9 THC. Both number of errors and length of time to complete the test were increased. The increase at the two higher dosages was statistically significant, but at the lower dose merely represented a trend.

Milstein *et al.* [1975] examined coordination skills in 16 experienced and 16 naive users of marihuana. There were 8 male and 8 female naive users and 8 male and 8 female experienced users. Subjects received either placebo or 7.8 mg delta-9 THC by smoking in a crossover design. There were six tests. Three required the subjects to move a stylus through a groove without touching the sides; with a straight groove oriented vertically, with a straight groove oriented horizontally, and with the groove in the form of a maze. A fourth task involved hand steadiness with a stylus inserted successively into nine hole sizes in a metal plate. These were then followed by two measures of motor ability; finger and toe tapping. While the finger and toe tapping tests showed no significant drug treatments, the four measures of hand steadiness and coordination exhibited statistically significant impairment. Strangely, there was a greater impairment among the experienced users than the naive users on the maze and hand steadiness tasks.

Kvalseth [1977] examined subjects on two coordination tasks. The first task required subjects to tap with a stylus back and forth between two parallel metal plates as fast as possible without either overshooting or undershooting the stylus plate. The width of the stylus plates was varied through the experiment. A second experiment involved a similar apparatus except that rather than moving the hand back and forth with the stylus, a rotary pointer was moved back and forth between the targets by turning a round control knob. Six subjects received each of three treatments; 0, 6.5 mg and somewhere between 19.5 and 19.6 mg delta-9 THC. Marihuana increased the error rate at all levels of task difficulty for both linear and rotary movements.

The above results are fairly consistent in demonstrating that marihuana impairs coordination as defined by increases in hand steadiness, body sway and accuracy of execution of movements. However, its relevance to complex skills typically required in driving and flying is limited. Individual variability in coordination has not been an important determinant of safety in interactions with most man–machine systems. Rather, other areas of impairment have been the usual cause of accidents. However, a sudden demand for a rapid avoidance maneuver to an obstacle in the path of a vehicle would be difficult to execute under marihuana. Given the safety margin in most transportation situations, the decrement in coordination is not likely to be the major cause of a marihuana-related accident.

This statement must be qualified by noting the relatively limited range of dosages studied, a matter which will be discussed later. It should be noted, however, that the impairments

produced by marihuana in hand steadiness, body sway, etc., could assist in the inclusion of such tasks in a law enforcement sobriety test in the same manner as similar functions are used to examine alcohol impairment. Similar to alcohol, it is relatively infrequent that the impairment in coordination, hand steadiness or body sway is an important factor in the production of automobile accidents, but it remains a symptom of other areas of impairment, so officers can identify an impaired individual.

Reaction time under marihuana

The effects of marihuana on reaction time have been studied in many settings with considerable variability in both stimulus and response required. One of the earliest studies was the LaGuardia report [Mayor's Committee on Marihuana, 1944] with 72 prisoners performing a test battery which included both simple and complex reaction time experiments. Unfortunately, the THC content of the orally administered cannabis was not known. A quite "large" dose, defined by subjective evaluation, produced only slight impairment of simple reaction time. Complex reaction time was impaired both by the large dose and a smaller dose 40% of the size of the larger.

Clark *et al.* [1970] examined complex reaction time to visual stimuli. The stimuli were four colors projected singly or in combination in four quadrants, with two possible response measures involving a finger or a foot movement. Eighteen subjects received an oral dose of 300 mcg delta-9 THC per pound bodyweight. A small overall increase in reaction time was found, with a more substantial increase in the variability of reaction times within subjects over trials. This increased variability in response under marihuana has been noted parenthetically by several investigators but rarely examined systematically.

Dornbush *et al.* [1971] examined 10 subjects who smoked marihuana at two dose levels; 7.5 and 22.5 mg delta-9 THC. Simple reaction time was measured in both visual and auditory modalities using a single stimulus with a single response. The lower marihuana dose failed to affect either modality reaction time, but there was a less than 10% increase in reaction time for both modalities for the larger dose.

Moskowitz *et al.* [1972] examined reaction time to stimuli presented over a wide degree of peripheral visual angles but requiring only a single response. The stimuli were presented for 1 second only. Twelve subjects were tested in a Latin square design at treatment levels of 0, 50, 100 and 200 mcg/kg B.W. delta-9 THC. Marihuana had a highly significant effect on the number of peripheral stimuli detected. However, if the stimulus was detected, there were no significant changes in the reaction time.

Moskowitz *et al.* [1974] examined 12 subjects under treatments of 0, 100 and 200 mcg/kg delta-9 THC in a psychological refractory period procedure. This involves the measurement of two reaction times to two stimuli presented in close time proximity to each other. The first stimulus was an auditory stimulus and the second was a visual stimulus. The time relationship between the first and second stimulus was varied. In this complex reaction time situation both doses of marihuana produced significant impairments of reaction time, with the greater impairment occurring to the second stimulus by a significant degree.

Borg *et al.* [1975] examined simple and complex reaction time using visual stimulus. In the simple reaction time the stimulus was always the same color, and in the complex reaction time the stimulus could be one of two colors, to only one of which was a response required. Five subjects received six treatments containing 0, 70, 130, 190 and 250 mcg/kg delta-9 THC or a no-smoking condition which served as a control for the placebo dose. The study was replicated four times requiring each subject to complete 24 test sessions in a Latin square design. Subjects had their right hand upon a switch plate, and when the visual signal occurred, lifted it from the first switch plate and made the response by touching a second switch plate. Separate analysis was done of time to react, i.e. to initiate the movement from the first touch plate, and the motor speed time to move from one plate to another. Both reaction time and motor response time were significantly impaired by marihuana, with motor speed the most impaired. There was a slightly greater degree of impairment for the complex reaction time in comparison to the simple reaction time. This also held true for the motor component.

In a study by Peters *et al.* [1976] 10 frequent and 10 occasional marihuana users received dosages of 0, 0.2, 0.4 and 0.6 mg delta-9 THC/kg B.W. orally. The test battery contained a

reaction time experiment involving four colored lights to which a subject responded by tapping a telegraph key to various predetermined configurations of the lights. Reaction time was increased for all active dose levels of drug treatment. While the authors define the task as simple reaction time, it is questionable whether this is a proper description.

Schaefer *et al.* [1977] examined 12 subjects after smoking marihuana containing 0, 10 and 20 mg delta-9 THC. The test battery included a complex reaction time experiment which involved responding to an oddity discrimination task. Subjects responded as quickly as possible to the odd element of a push button display. There were three push buttons, one or two of which were illuminated on each trial. The subject was required to respond to the odd lit or unlit button as rapidly as possible. The experiment involved two conditions, either the subject was told in advance whether the odd button would be lit or unlit, or this information was withheld. If the subject knew what the state of the task was, there was an insignificant trend towards an increased reaction time under marihuana. When the uncertainty of the task increased, the marihuana treatment was statistically significant in increasing reaction time.

A study of Peeke *et al.* [1976] examined the interaction between practice and marihuana treatment on reaction time. There were 14 subjects in two groups of 7 each. Drug treatments were placebo and 18 mg delta-9 THC by smoking. There were three complex visual reaction time tasks. The first task involved time in making a judgment whether two stimuli, which succeeded themselves in time, matched in two attributes of color and form. In the second task, one of five geometric forms was presented in central vision and five comparison forms were presented over a visual angle of 48 degrees, with the subjects required to indicate which of the five comparison stimuli matched the central one. The third task involved performing the second task while simultaneously responding on half of the trials to an auditory stimulus. One group performed the tasks on four consecutive sessions under marihuana and then on a fifth day under a placebo treatment. The second group performed the tasks for four consecutive days with a placebo treatment and then under marihuana on the fifth day. The group that had four undrugged practice experiences before the marihuana treatment showed no effect of marihuana treatment on the reaction time. The group which received the four treatments on the marihuana first showed a significant reaction time impairment on the first day only. The authors suggest that a practiced reaction time task is insensitive to drug effects, whereas an unpracticed task initially is sensitive to drug effects due to a possible effect on attention processes. They suggest that tasks which are well practiced have become automated and are therefore more resistant to drug effects.

Rossi *et al.* [1977] examined 12 casual and 15 heavy users of marihuana who lived in a hospital ward for 31 days. On 21 days they were free to smoke any quantity of marihuana they wished. On each day they performed a battery of tests which included a simple and a choice reaction time task. The reaction time apparatus involved four response keys, one of which was to be pressed when a corresponding stimulus was presented. In the simple case the subjects knew in advance which stimulus and key were to be used. In the choice reaction situation the subjects did not know which of the four stimuli would be presented and, in addition, there were five alternate stimuli presented on a display which required no response. Subjects were tested under both marihuana conditions and control conditions over the 31-day period. No differences were found due to the marihuana treatment or between heavy and casual users. The authors did remark on the large variability in performance under marihuana treatment.

A study by Kvalseth [1977] utilized six experienced marihuana users as subjects at three dose levels; 0, 6.5 and between 19.5 and 26.0 mg delta-9 THC. The reaction time task was a complex reaction time, with the subject required to respond to one of a variety of visual stimuli by pressing the appropriate button. The complexity of the task was manipulated by varying both the number of possible stimuli which could occur and the probabilities with which they occurred. The number of possible stimuli were one to eight. The experiment was conducted within the context of an analysis based on information theory, with the calculation of the amount of information transmitted by the subjects. The amount of uncertainty in the stimulus set had 13 different values in the interval from 0 to 3 bits. The drug condition had no significant effect on the simple reaction time, i.e. the case of one stimulus and one response. Nor was there any relationship between the marihuana dose level and performance as the complexity and amount of information were increased.

Stillman *et al.* [1977] examined 24 marihuana users after a placebo treatment and after smoking marihuana containing 15 mg delta-9 THC on a complex reaction time task. Subjects were to respond as fast as possible with a key response if a designated target stimulus was presented to peripheral vision. The target stimulus fell into two categories. There were two verbal trigrams, i.e. three letter stimuli, calling for responses, and two which called for no responses. Also, two sets of faces which called for responses and two which called for no responses. The stimuli were presented tachistoscopically to the left or right visual hemisphere, so that the stimuli would be initially presented to either the left or right hemisphere. Thus the experiment examined the interaction between type of stimulus, verbal or not verbal, left or right hemisphere, and presence or absence of marihuana.

There was a significant marihuana-induced change in laterization, with the faces stimuli, i.e. picture stimuli, but not with the verbal stimuli. Reaction time under marihuana to picture stimuli was impaired in both visual fields but there was a significant right hemisphere superiority after marihuana smoking which was greater than the superiority found when under nonmarihuana smoking. Thus, there was a triple interaction between type of stimulus, hemisphere initially stimulated and drug state.

While the above experiments dealing with reaction time certainly could not be said to be exhaustive of the entire literature, several tentative conclusions appear justified. In a sense, the original LaGuardia report was correct. There seems little evidence that simple reaction time is impaired. However, it appears less certain that complex reaction time is necessarily impaired, *per se*. Reaction time, whether simple or complex, is an insufficient description of the varying complexities inherent in a situation in which an observer must detect and recognize stimulation, organize and execute a response, especially to complex stimuli requiring a complex response. The cognitive demands of a reaction time situation vary considerably. It appears that some cognitive demands *are* sensitive to the effects of marihuana. There are a sufficient number of experiments involving both simple and complex reaction time situations to leave us relatively well assured that neither the speed of initial detection nor the speed of responding are, *per se*, impaired by marihuana. Rather, when marihuana produces a reaction time increase, there is some dimension of the information processing task which the subject must execute which bears the brunt of the impairment.

There is nothing about the preceding review of reaction time experiments which will suggest what the nature of that impairment is or where its CNS or behavioral site of action is. However, the frequency of reports of great within-subject variability in performance of reaction time experiments under the influence of marihuana hints that at least one locus of impairment might be attention mechanisms.

Tracking under marihuana

Tracking is an important component of many skilled man–machine interactions, such as driving, flying and some machine controlled activities in industry. Laboratory studies of tracking frequently differ in both the stimulus presentation and the response mechanism as a function of interest in modeling different tracking systems. The two major differences among tracking tasks found in the drug studies reviewed are between pursuit and compensatory tracking. In pursuit tracking, the tracker can see the movement of the object to be tracked as well as the tracking device; for example, a spotlight on an actor on the stage.

In compensatory tracking tasks, only the error—the difference between the output of the tracking device and the tracked object—is displayed. An example would be a requirement to maintain a spot on an oscilloscope screen at the center of that screen in the face of displacing movements. The tracker can observe how far the light is from its correct position, but cannot independently observe the forcing function which is displacing the object nor his compensating movements directly. Automobile driving is an example of compensatory tracking tasks.

A simple version of a pursuit tracking task, the pursuit roter, was utilized by Weil *et al.* [1968]. Nine naive subjects who had never used marihuana and 8 heavy users were tested under three dose levels of delta-9 THC, 0, 4.5 and 18 mg administered by smoking.

There were significant decrements in the performance of the naive subjects on both active doses at 15 and 90 minutes after smoking, while the chronic users showed no impairment.

However, more demanding pursuit tracking studies have consistently found decrements in performance, often at lower dose levels.

Manno *et al.* [1971] examined pursuit tracking behavior. An oscilloscope presented pursuit tracking tasks at four levels of increasing complexity. Twelve male subjects smoked cigarettes containing 0, 5 and 10 mg of THC on separate occasions. Both the low and high dosages produced significant impairment at all four levels of pursuit tracking complexity. Using the same apparatus, Kiplinger *et al.* [1971] found similar results for smoked marihuana treatments, which the authors believe delivered to subjects 6.25 to 50 mcg delta-9 THC/kg B.W.

Evans *et al.* [1973] examined very low doses of marihuana on the same pursuit tracking task employed by Manno *et al.* [1971] and Kiplinger *et al.* [1971]. Treatments were 0, 3, 6 and 9 mcg/kg THC delivered, based on the assumption that subjects receive half of the dose presented. Beginning at the lowest dose level, there was significant impairment of performance on the tracking task.

A study by Roth *et al.* [1973] employed another tracking task, a contour tracking task. A contour tracking task shows the path of the points to be tracked, so that the subject has preview information. Thus, it is possible to anticipate and organize responses over a longer time period than in the pursuit tracking described above. Eighteen subjects received a brownie containing 20 mg of delta-9 THC and 19 subjects received placebo. The marihuana treatment significantly increased the magnitude of error in following the track.

Reid *et al.* [1973] examined the effect of 0, 21 and 88 mcg delta-9 THC/kg B.W., presented in the form of smoked marihuana, on a compensatory tracking task. Subjects performed six tracking runs which were used for the analysis. The data were analyzed in terms of human operator tracking characteristics models which involve the use of linear mathematical models to describe the manner in which the human operator responds with his output to a known complex input. The data compare the amplitude and phase differences between the input of the forcing function and the output of the human operator at each frequency component of the input. While the data indicated only minimal changes in the phase angle and amplitude of response for subjects under marihuana, there was a significant increase in the appearance of responses which were uncorrelated with any input aspects. As the authors suggest, it was as though there were an increase in random noise.

Sharma and Moskowitz [1975] examined 12 subjects on a critical tracking task under both placebo and 200 mcg/kg THC. A critical tracking task is a form of compensatory tracking which continually increases in instability and difficulty during the trial, so that at some point its instability is beyond the capacity of the subject to control. At that point the trial ends. Trials are extremely short, well under 1 minute, and it is possible to give many trials within a short period. In this case the subjects performed blocks of 12 trials at 15-minute intervals over a 4-hour period. Subjects showed statistical impairment on this task over the entire 4-hour period.

Moskowitz, Sharma and Ziedman [1981] examined a performance test battery at 13 time points over a 20-hour period following a single dose. The eight subjects received treatments of 0, 50, 100 and 200 mcg/kg B.W. delta-9 THC by smoking. The battery included a compensatory tracking task performed while simultaneously executing a visual search task as well as a critical tracking task. Performance was significantly impaired on the compensatory tracking task for more than 2 hours and upon the critical tracking task for up to 10 hours, albeit, intermittently during the period from 4 hours on.

Burns and Moskowitz [1980] examined the effects of 200 mcg/kg B. W. delta-9 THC in comparison with placebo on a critical tracking task, compensatory tracking task alone and a compensatory tracking task while in a divided-attention situation with a visual search task. All measures of tracking were impaired in the 1-hour period of testing.

While this review of tracking is not exhaustive, it is clear that tracking is an area of psychomotor performance which is highly sensitive to the decremental effects of marihuana over a wide range of dosages and over an extended duration. Since tracking is an important component of driving, flying and many other man–machine interactions, these findings are of considerable social significance. It is interesting to note the contrast between the infrequent findings of performance decrement on reaction time tasks under marihuana in contrast to the unanimous reports of impairment of the tracking tasks. While both are sensory-psychomotor

tasks, it is clear that there is an additional factor in the tracking situation which makes it susceptible to performance decrement by marihuana. One obvious difference is that tracking tasks are not intermittent, they are continuous in their demand for attention to the task in contrast to reaction time tasks which are presented intermittently. However, this is a speculative comment, and, clearly, the issue of why there is this difference in impairment has yet to be understood.

Sensory and perceptual functions

Caldwell *et al.* [1969] compared sensory performance for auditory and visual thresholds in 20 subjects. Subjects received a control substance cigarette made of alfalfa and an active treatment cigarette which they smoked until they achieved a high. The mean amount of marihuana consumed to reach a "high" was 6.337 mg delta-9 THC. The behavioral battery included four tests; a visual comparative brightness task, an auditory threshold task, an auditory differential intensity threshold task and an auditory differential frequency threshold task. There appeared, in the words of the authors, to be a minimal effect on measures of sensory acuity. No effect was found on the visual brightness comparison, a small statistically significant effect on the auditory differential intensity threshold, and small but not statistically significant effects on the auditory differential frequency threshold or auditory absolute threshold.

Moskowitz *et al.* [1972] examined 12 subjects on a battery of visual tasks in a 3 × 3 Latin square design with three treatments, placebo, .69 gm alcohol/kg B.W. and 310 mcg delta-9 THC/kg B.W., in an alcohol solution oral dose. The visual functions examined were dark adaptation, visual acuity, fusion and vergence responses. The length of time necessary for subjects to dark adapt after being light adapted was reduced slightly but not statistically significantly by both alcohol and marihuana.

Visual acuity was assessed at a fixation distance of 6 meters and also showed no difference in the resolution of targets under marihuana. While a test for binocular fusion was not affected, the test of lateral and vertical phoria found significant effects of both alcohol and marihuana on lateral phoria, although not on vertical phoria. This would suggest that under alcohol and marihuana it would be more difficult to maintain single vision, but to only a slight degree at these dose levels. It should be noted that these problems are not the effect of drugs on sensory processes but rather upon oculomotor control. A duction test, which measured lateral and vertical fusional vergence movements, again found that under the abduction condition there would be increased difficulty in maintaining fusion under marihuana or alcohol.

The results of these experiments showed little influence on visual transducing or sensory transmission mechanisms but a small impairment of oculomotor control at these dose levels.

Adams *et al.* [1975] examined static visual acuity at two contrast levels in 10 subjects with five treatments; placebo, two marihuana and two alcohol dose levels. The marihuana treatments were 8 and 15 mg of delta-9 THC. Subjects were examined for six hours following drug ingestion, and at no point were there any significant changes in static visual acuity. This result contrasts with a similar experiment which they performed. There they found significant effects upon dynamic visual acuity, which is acuity in resolving the characteristics of a moving target.

Adams *et al.* [1978] examined the effect of marihuana, alcohol and their combination on glare recovery time after an intense light exposure. The alcohol treatment was .96 gm/kg B.W. alcohol, the two smoked marihuana treatments were 8 and 15 mg delta-9 THC, and the combined treatment was the alcohol dose with 15 mg delta-9 THC. There was a small but statistically significant increase in the duration of recovery time, 6% for the 8 mg THC dose and 8% for the 15 mg dose. In comparison to the marihuana-only treatment, there was a further small increase in impairment under the combined alcohol–marihuana treatment. The authors suggest that the nature of the impairment might be due to some retinal process.

Adams *et al.* [1976] examined the effects of alcohol and marihuana on color discrimination with marihuana treatments of 8 and 15 mg delta-9 THC, and alcohol treatments of roughly .5 and .8 gm/kg B.W. The larger spectral shift occurred in the blue region for both alcohol and marihuana, which might cause some slight confusion of blues with blue/greens. In addition, marihuana produced a lesser change in the red/yellow region and alcohol in the yellow/green region. The authors suggest that the color discrimination reductions resemble those seen in

acquired color vision defects associated with retinal disease which, again, suggested that the drug effect site might be retinal. The duration of marihuana effect was less than 1 1/2 hours.

A study by Thaler *et al.* [1973] examined 11 subjects on a battery of audiometric tests under controlled and marihuana treatments. The marihuana treatment was specified in terms of the subjects subjectively achieving a satisfactory "high." In a variety of tests of speech discrimination using word lists, both in quiet and in white noise conditions, subjects under marihuana significantly improved their ability to discriminate speech.

Hill *et al.* [1974] compared the effects of smoking approximately 12 mg delta-9 THC marihuana in a group of 20 subjects to a placebo group of 6 subjects upon the threshold for sensation and pain to electrical stimulation as well as upon pain tolerance. The treatments heightened sensitivity to the electrically produced painful stimuli, with subjects showing lower threshold for sensation and pain and decreased tolerance. On the other hand, Milstein *et al.* [1975] reported a trend towards an increase in pain tolerance under marihuana.

Schwinn *et al.* [1974] examined 30 subjects divided into two groups on critical flicker fusion frequency thresholds. The active treatment was 15 mg delta-9 THC by smoked marihuana. An enhancement of the critical flicker fusion occurred, i.e. under marihuana an increase in flash frequency was necessary to produce fusion of roughly 1.33 cycles per second. The authors note that a similar result had been reported for Benzedrine, a stimulant.

While the above survey is not exhaustive, it appears that some sensory functions show slight impairment under marihuana, but of a magnitude unlikely to be an important factor in complex man–machine interactions such as driving or flying, except under extreme conditions. This comment is being made with respect to simple sensory functions and does not include possible effects of marihuana on the oculomotor system nor upon such functions as dynamic visual acuity which might properly be called a complex task involving more central functions than the simple sensory discrimination above. The following studies will examine functions more properly designated as perceptual and requiring presumably more complex information processing.

Sharma and Moskowitz [1972] examined the effects of four dose levels of marihuana, 0, 50, 100 and 200 mcg delta-9 THC/kg B.W. in 12 subjects upon the visual autokinetic phenomenon. The visual autokinetic phenomenon is the illusionary apparent motion of a stationary source of light in a darkened environment free of spatial references. There was a dose-related increase in apparent movement, with a trend at the lower dose and statistical significance for the higher doses. The two larger treatments doubled and tripled the amount of apparent movement.

Moskowitz *et al.* [1972] examined the effect of marihuana on peripheral vision as a function of concurrent activity in central vision. In this study subjects fixated upon a central light while occasional light sources were illuminated at points in a visual arc of 204 degrees centered about the central fixation light. The experiment was run under three levels of information processing demand for the central vision; either no blinks, slow blinks or fast blinks of the central light, which the subjects were required to count in 20 second trials. A subject was required to respond as rapidly as possible to the presentation of each peripheral light stimulus which was on for one second. Under all three levels of information processing demand for central vision, peripheral signal detection was significantly and greatly impaired by 50, 100 and 200 mcg delta-9 THC in comparison with placebo. As mentioned earlier, there was no effect on the reaction time in responding to the signals seen, but a very large drop in the number of signals perceived.

The three active marihuana treatments produced 8, 20 and 50% increases in missed signals over the placebo treatment. There was also an increase of errors in counting of the central light blinks with the marihuana treatment. Finally, there was a greater degree of impairment with the faster blink rate, i.e. under the greater demand for information processing.

A similar experiment by Caswell and Marks [1973] examined 20 subjects, 10 experienced and 10 naive, under 0, 3.3 and 6.6 mg delta-9 THC using an apparatus similar to that used by Moskowitz *et al.* [1972] with a smaller visual angle. Dose-related large impairments were found in misses of both the central light signal and the peripheral light signals, with roughly equal impairment for both naive and experienced groups. As mentioned earlier, a study by Moskowitz *et al.* [1974] examined the effect of marihuana on the psychological refractory period. This is the increased delay in reacting to the second of two signals in close temporal

proximity to each other. The second response is slower because of delays from processing the first signal through the central nervous system. A differential effect of marihuana on the two reaction times was found which implied marihuana impairment of information processing consistent with the increased impairment of visual perception in the above experiments.

A study by Moskowitz and McGlothlin [1974] examined the effects of marihuana on auditory signal detection under two levels of attention demands. Twenty-three male subjects were examined under five treatment conditions, one with no smoking and four with smoked marihuana containing either 0, 50, 100 or 200 mcg delta-9 THC/kg B.W. Signal detection was measured under conditions of concentrated attention in which subjects reported the presence or absence of a tone in a 3-second noise burst, and with divided attention where the subject also repeated a series of six digits presented simultaneously with the noise burst. No differences were found between the no treatment and placebo conditions. There was a significant dose-dependent impairment of signal detection for the marihuana treatments under both concentrated and divided attention conditions. Application of signal detection theory suggested that the impaired performance was primarily due to a decline in perceptual sensitivity, [d']. There was a small indication of criteria change with a greater tendency for erroneous reporting of a signal when it was not present, a result which has also been reported in short-term memory studies.

In a perception study by Jones and Stone [1970], five treatments were administered; placebo, alcohol, smoked marihuana both active and placebo, and an oral dose of cannabis. The oral dose of marihuana was apparently 9 mg delta-9 THC and the smoked dose half that. The authors report that while time estimations were changed, the rod and frame perceptual test was unimpaired.

Moskowitz *et al.* [1976] examined visual search behavior while viewing driving scenes in a film presentation driving simulator under the influence of alcohol and marihuana, separately. The marihuana treatments were 0 and 20 mcg/kg B.W. THC. The study examined a variety of measures of visual search behavior using an eye movement recording device. While alochol produced highly significant and large impairment in performance, none of the variables which were significant for alcohol was impaired by the substantial marihuana dose. For example, neither the mean time for fixations or pursuits nor the frequency of pursuits and fixations were significantly affected. It should be noted that these response variables for eye movement are frequently considered a measure of speed of information processing or cognitive function, not an indication of their accuracy.

Sharma and Moskowitz [1973] examined vigilance behavior in the performance of a simple visual detection task over an extended period of time. Twelve subjects were examined under smoked marihuana with doses of 0, 50, 100 and 200 mcg delta-9 THC/kg B.W. Subjects observed light bulbs placed on a 12'' diameter circle. These light bulbs lit successively except occasionally a position was skipped and the next position lit. This constituted a signal to which the subject was to respond. The two largest dose levels produced extremely large and significant impairments of performance, with the magnitude of impairment increasing over a 1-hour period. While there was a trend for impairment under the 50 mcg condition, it was not statistically significant.

In a subsequent study by Sharma and Moskowitz [1974], this same task was administered under two attention conditions with two treatments, 0 and 200 mcg delta-9 THC/kg B.W. in 12 subjects. In the previous experiment, responses only had to be made to the target signal, e.g. the double position jump. In this study there were two conditions, one which duplicated the previous experiment and a new condition which required that one hand respond to all light changes which were not targets and the other hand respond to the target signals. This increased the demand for attention to the task and produced an increase of performance. However, the decrement produced by marihuana under such condition was the same with respect to that condition. That is, the impairment due to marihuana was of the same magnitude for both conditions and was unrelated to the demand for attention, although under the high attention condition the overall performance was better. Thus, whatever the nature of the marihuana deficit is, it would not be due to lack of attention.

A study by Baloh *et al.* [1979] examined the effect of alcohol and marihuana on oculomotor control using eye movement recording. Twenty-four subjects were given treatments of 0 or 100 mcg delta-9 THC/kg B.W. at three different blood alcohol concentrations, 0, 0.05 and

0.10%. Saccades, smooth pursuit and autokinetic nystagmus were evaluated. Saccades and smooth pursuits were induced by observing a dot of light moving in steps and ramps on a cathode ray tube. Optokinetic nystagmus was induced by a cloth drum surrounding the subject and moving at a constant velocity of 30 degrees per second.

While alcohol at both doses produced significant impairment of saccade, maximum velocity and reaction times, smooth pursuit velocity and optokinetic slow component velocity, there was only a trend which was not statistically significant for marihuana alone to have similar effects. There was also a trend which was statistically insignificant for marihuana to increase the effects of alcohol deficit on these performance measures.

To sum up, it is clear that many perceptual functions are significantly affected by marihuana. However, the dimension of complexity versus simplicity is insufficient to differentiate between which tasks are affected by marihuana and which are not. Clearly, in many of the tasks which are prototypes of perceptual demands met in man–machine interaction such as in the signal detection studies, very large decrements of performance occur representing a potential threat to the marihuana use and to others in his environment. But it is not clear why some tasks are impaired and others are not. The small deficits in oculomotor control are consistent with the small deficits in simple reaction time and in body sway situations. Why the visual search study using eye movement failed to uncover impairment using variables indicative of cognitive function is not clear, especially in view of the many perceptual tasks which were highly impaired. Clearly, our understanding of the nature of marihuana-induced impairments remains limited, but it is equally clear that perceptual performance is greatly impaired.

Simulator studies of marihuana

A driving simulator is a laboratory instrument requiring the subject to perform a sample of some of the behaviors involved in driving. Simulators differ from most of the laboratory studies above in the greater complexity of the behaviors sampled. More stimulus and response elements are sampled, thus making the simulator more representative of the multitask character of driving. However, it should be noted that no simulator is capable of representing *all* the aspects of driving simultaneously. Rather, it is only a subset of the behavioral demands of driving, and that subset varies from simulator to simulator as a function of the interest of the investigator and the stage of technological development of the simulator. In comparison to car driving situations, the simulator has the advantage of repeatability of stimulus presentation to all subjects.

The earliest simulator study with marihuana by Crancer *et al.* [1969] examined 36 subjects under three treatments; a smoked 22 mg delta-9 THC marihuana treatment, alcohol to produce 0.10% BAC and a nontreatment situation. Subjects sat in a mockup of a car viewing a 23-minute film. While the subject was instructed to manipulate the steering wheel, turn signals, brake and accelerate in response to the film presentation, these actions produced no effects except for the accelerator which controlled the speedometer reading. The subject was required to maintain the speedometer reading within prescribed limits. The other measures were appropriate responses to the film when it appeared to require a stop, turn or some other maneuver.

While alcohol affected four of the five response measures, only the speedometer measure showed increased errors under marihuana. However, it should be noted that the speed of the film presentations was not under the control of the driver and that, therefore, speedometer errors were merely an indication of the amount of time spent monitoring the speedometer.

The increased number of errors in maintaining the speedometer within the prescribed limits suggests an effect of marihuana upon the subject's monitoring of this instrument, and its impairment agrees with many studies indicating perceptual impairment by marihuana. The failure of marihuana to affect the other measures is difficult to evaluate since it is not clear what these measures are a sample of, either in the driving situation or as descriptions of categories of behavior. It should be further noted that Kalant [1969] has specifically criticised this study for its experimental design and drug treatments. Moreover, Manno *et al.* [1971] suggest the possibility that the marihuana dose administered may have been less than intended.

Rafaelsen *et al.* [1973] and Bech [1972] also used a car mockup (a Redifon Auto-Tutor) which had a windshield upon which was projected a moving landscape from a painting on a drum which was illuminated by a projector. This simulator was equipped with steering wheel,

accelerator, brake, gear shift and clutch. The speed of movement of the landscape was controlled by the accelerator while the steering wheel shifted the site of the image on the windshield, providing a tracking task. Mounted above the windshield were green and red traffic lamps. The subject was instructed to stop the car whenever the red light appeared and to start again upon the appearance of the green light. The duration of the red light was always 10 seconds and it appeared ten times during the 10-minute drive at random intervals.

The response measures were start time, brake time, number of gear changes and mean speed. Break and start times represented the response latency to the appearance of red and green lights. The eight subjects received four drug treatments; 70 gm of alcohol and oral doses of 8, 12 and 16 mg delta-9 THC. The marihuana was ingested in the form of a baked cake. Significant changes occurred in the latency of response to the lights under both alcohol and marihuana. While the 8 mg marihuana dose had no significant effect, the 12 and 16 mg doses produced large increases in latency, with the alcohol treatment being midway between the 12 and 16 mg THC dose in magnitude of impairment.

While the number of gear changes was affected to a small but statistically significant degree by alcohol, marihuana had no effect. Mean speed was uninfluenced by either drug.

Moskowitz *et al.* [1976] utilized a simulator with a car mounted on a chassis dynamometer facing a 20-foot-wide film screen subtending a 160-degree visual angle. A 31-mile filmed route was driven by subjects at their desired speed through use of brake and accelerator. A tracking task was included requiring the subject to manipulate the steering wheel to follow the contours of the road. In addition, a visual subsidiary task required responding to the appearance of four possible colored light signals, two on each side. Steering wheel, accelerator and brake position were used to derive 25 performance measures of speed, accelerator, brake and steering wheel usage as well as tracking error. Twenty-three subjects received four drug treatments in the form of smoking cigarettes containing 0, 50, 100 and 200 mcg delta-9 THC/kg B.W. None of the tracking or car control measures showed significant decrements under marihuana, but the subsidiary task was extremely sensitive to drug effects, with significantly greater number of incorrect responses and increases in reaction time to the appearance of the lights.

All three of the above studies produced evidence of marihuana affecting performance related to the perceptual demands of driving, with only small evidence of tracking or car control influence. However, it should be noted that the demands for car control or tracking in these simulators were of a limited character. That is, the roadway is fixed by the nature of the film which presents the pathway independent of whatever the subject may decide to do in his tracking.

In contrast, a recent driving simulator study by Smiley *et al.* [1981] reexamined the car control issue in an interactive computer-controlled simulator. In this simulator, the image is generated by a computer which permits a closed-loop interaction with the driver and a very accurate representation of the tracking demands of actual driving over a wide range of roads. This study utilized a 3×3 factorial design with three levels of alcohol, 0, 0.425 and 0.68 gm alcohol/kg B.W., delivered by smoked cigarettes. There were three separate groups of 15 subjects at each alcohol leve, but all three marihuana levels were administered to each subject. Because of dropouts, only 35 subjects completed the study.

Driving sequence included curves, windgust situations, car following situations where subjects were rquired to follow other cars at a certain distance behind while the lead car varied its speed, car passing situations, route sign recognition and emergency obstacle situations. Marihuana produced significant changes in the variability of velocity and of later position while going around curves and while experiencing windgusts. There was increased variability of headway and lateral position while following cars. There was a decrease in the number of turnoffs taken successfully in response to route signs, there was an increased variability of lateral position during overload conditions, and an increase in the reaction time to the appearance of peripheral lights requiring responses.

The tracking data was examined using a power spectral analysis and a modeling of the car-driver transfer function. Under marihuana, coherence or the correlation between the tracking demands of the road and the driver's control responses decreased. This would result from random or inappropriate changes in steering responses. During the ride, an obstacle suddenly appeared requiring an emergency response. Under marihuana there was a significant increase in the numbers of subjects having crashes at the high dose. In the car passing sequence, which

occurred in the face of an approaching car, marihuana induced a more conservative behavior, with the subjects only attempting the task with a greater than normal distance to the approaching vehicle. Thus, in this simulator which places a greater demand on car control and tracking ability in contrast to the visual search-and-recognition aspect of driving, there was clear evidence of marihuana's decremental effects on tracking. These results are consistent with the results of actual car tasks, which will be discussed in the next section.

The experiment above contained a measure of risk-taking behavior. Two other simulator studies have emphasized the examination of risk-taking behavior. Dott [1972] used a simulator which projected a scene from model cars moving on endless belts simulating two car lanes. Subjects were required under certain conditions to attempt to pass a car in their lane by crossing into the passing lane prior to the approach of a car from the opposite direction in that lane. The experiment had some additional variables including a signal indicating the necessity for aborting a pass maneuver, and an additional signal which indicated that a successful passing maneuver would require a very rapid response.

Twelve subjects were examined under four treatments; smoking marihuana containing 0, 11.25 and 22.5 mg delta-9 THC in addition to one treatment of no smoking. Similar to the Moskowitz *et al.* [1974] study quoted above, no differences for any objective measure occurred between the placebo treatment and the no-smoke condition which controlled for placebo effects. The marihuana treatment caused an increase in the frequency with which subjects aborted passing maneuvers when a warning signal was presented. Moreover, there was a decrease in attempted passes and no effect on the execution of a passing maneuver if attempted. The path lengths for the passing maneuvers showed no differences. However, under marihuana there was an increase in the time subjects required to make a decision to attempt to pass when the opportunity appeared. This occurred only in the nonemergency situations. Decision times on the emergency warning signal remained the same for all treatments.

Ellingstad *et al.* [1973] also examined risk-taking under the influence of marihuana and alcohol. Six groups of 16 subjects received the following treatments: 11.25 and 22.25 mg delta-9 THC, alcohol producing 0.05% and 0.10% BAC, and two placebo groups composed of marihuana and nonmarihuana users. Two tasks comprised the experiment. In the first task, film presentations presented the minimum amount of time necessary to make an overtaking maneuver of a car traveling in front of the subject. Then, a series of test films followed in which the subject indicated the last time point in which he felt a safe maneuver could be made to pass in the face of an approaching car. No actual overtakings were attempted. Both marihuana doses produced earlier cutoff times—subjects refusing to attempt passing at times when subjects under placebo conditions would have done so. Moreover, subjects less frequently performed overtaking that would have been considered unsafe based on objective time differences between the two vehicles.

The author suggested that rather than changing risk-taking, marihuana produced a deficit in time estimation. However interpreted, it is clear that there is consistence among reports that under marihuana drivers are less likely to make risky overtaking maneuvers, whether due to a realization of their impairment, a direct pharmacological influence on attitudes, or a fortunate happenstance of the nature of the impairment of time estimation.

In sum, while the simulator studies suggest more conservative behaviors under the influence of marihuana, all studies examining objective measures of driving performance report impairment of driving skills. These impairments have occurred in both the perceptual and car control areas as a function of the nature of the demands placed upon the driver in that particular simulator. The variation in the behavioral measures impaired in these studies can either mean that there were no sensitive measures of these behaviors in some simulators or that the behavioral area of impairment occurs in whatever behavioral area is under the greatest stress for performance. This latter explanation would place the actual behavior site of impairment in some central behavioral function common to both perceptual and motor skills performance.

Marihuana effects on flying

An additional simulator study examined marihuana's effect on simulated flying ability [Janowsky *et al.*, 1976]. Ten pilots operated a model ATC-510 instrumented flying simulator. Subjects ranged from infrequent to moderate marihuana users. Subjects performed four 4-

minute sequences involving maneuvers typically encountered in instrumented flights, both straight and level flights, turns, maneuvers, radio navigation, in the face of a low-level turbulence introduced into the simulator. Each sequence had a series of instructions for the performance which the subjects were to execute. Subjects performed in a crossover design smoking cigarettes containing either placebo or 90 mcg delta-9 THC/kg B.W. Performance measures which demonstrated decremental effects of marihuana were difficulty in maintaining designated altitude, heading, monitoring course deviation indicator and the production of both major and minor errors. Six of the pilots were tested over a 6-hour period, with performance not returning to normal until 4 hours had passed. The authors considered this a relatively simple flight task situation and suggested that impairment would be more likely in actual flying situations. The most important symptoms involved the impairment of short-term memory, with subjects often forgetting where they were in a given flight sequence. Attention and concentration were impaired so that dropouts of attention would occur with the subjects unable to recall where they were in executing their task sequence.

Marihuana effects on driving performance in automobiles

Several studies have been performed with subjects under the influence of marihuana driving a car either on closed courses or in traffic. An early pilot study performed at the North Carolina Highway Safety Research Center, under the direction of Dr. John Allen [Anonymous, 1972], utilized a closed course defined by traffic cone configurations. In a crossover design, 11 subjects drove the course twice, once after receiving an unstated oral dose of THC and, on another occasion, after receiving a placebo administration. No differences were found between the two treatments, either in the number of cones struck or in measures of braking, steering, accelerator and speed change. Interpretation is difficult since neither the course, the dose, nor the measures were described.

Hansteen *et al.* [1976] performed a more extensive closed-course study for the Canadian LeDain Commission Report. Subjects drove an automobile six times around a 1.1 mile course set out on an airfield. The course had both curve and straight sections as well as an area where subjects performed forward and backward maneuvers in a tightly constrained area. On part of the course the subjects maintained a speed of 25 miles an hour and in other parts they were permitted to drive as quickly as possible without exceeding 30 miles per hour. The course was defined by cones and poles and performance was scored on the number of hits of the poles and cones, driving time around the course and smoothness of handling as reported by an in-car observer. There were 12 male and 4 female subjects with marihuana smoking experience of from one to four years and current usage ranging from daily to once a month or less.

The four treatments administered in this double-blind Latin square design were placebo, 21 and 88 mcg delta-9 THC by smoking, and alcohol producing .07% BAC. At all sessions subjects drank a beverage followed by smoking a cigarette. They were tested immediately after completing the cigarette on the six laps described above and, subsequently, three hours later on a set of three laps. The mean number of struck objects per lap increased from a mean of 13.2 under the placebo to 13.4 under the lower marihuana treatment, to 16.8 for the higher marihuana treatment, and 17.4 for the alcohol treatment. Both the higher dose marihuana treatment and the alcohol treatment produced statistically significant impairment.

Rough handling described as superfluous or awkward movements, as observed by the in-car observers per laps, were 1.7 for placebo, 1.9 for the low marihuana dose, 2.2 for the higher marihuana dose and 2.7 for alcohol. Mean speed around the course dropped under the influence of the treatments. Performance during the second trial given 3 hours after smoking were in the same direction, although of a lower magnitude, with the increase in the number of hits still statistically significant but not the increased lap times.

The authors conclude that the driving study shows a decremental effect of the higher marihuana dose upon car handling, as measured by the objective performance scores, although there were only small differences in the handling scores as graded by observers.

A more extensive double-blind study was performed by Klonoff [1974] in which subjects performed both on closed courses and on city streets. The study utilized 64 subjects, 43 males and 21 females, all of whom were examined on the closed course with 38 also tested on the streets. Marihuana treatments administered by smoking were placebo, 4.9 and 8.4 mg delta-9

THC. The closed course study used a random group design, with 16 males and 5 females receiving the placebo, 13 males and 8 females receiving the 4.9 mg dose, and 14 males and 8 females receiving the 8.4 mg dose. The streets trials involved a within-subject design with each subject receiving both an active treatment, either high or low dose, and the placebo. Five males and 4 females received a low dose followed by the placebo, 7 males and 3 females received the placebo and then the low dose. Six males and 2 females received a high dose followed by the placebo, and 7 males and 4 females received the placebo followed by the high dose.

The closed course consisted of eight tests: A Slalom, two tunnel tests, a funnel test, a risk-judgment test, a backing up, a turning in a corner and an emergency braking test. Response scores were the number of cones struck, except for the risk taking and braking tests. Subjects received 20 trials in blocks of 5. The first 3 blocks were considered learning trials and were used to establish an expected score by a regression analysis for comparison with the fourth block. Thus, the three treatment groups were not compared with each other, rather, the mean attained score for the fourth block of trials in each group was compared with the expected score calculated for that group. The rather unusual data treatment requires the assumption that the learning curve for the initial 15 trials will continue in a linear manner to describe the succeeding 5 trials where no active treatment was administered. Notably, the placebo treatment scores in the last 5 trials showed considerable variation, although not in a statistically significant fashion from the expected mean. Using this analytic technique, the authors concluded that two of the eight tests, one tunnel test and the corner test, were impaired under the low treatment dose; five tests, the Slalom, two tunnels and the risk taking task, were impaired under the higher dose. While the mean of the impairment was not large, there was a clear trend for impairment under the active treatments.

In the city street driving session a variety of different traffic conditions was met in a 16.8-mile course. The tests were conducted during daylight hours and averaged 46 minutes. Scoring of subjects' performance was undertaken by observers in the car using behavioral scales of the British Columbia Department of Motor Vehicles. Difference scores between the placebo and drug treatments on each of the behavioral dimensions for each subject were converted to a transformed seven point scale for statistical treatment. While the larger marihuana dose group showed a significant decline, the lower group did not. The behavioral scales treat deviation in either direction from the placebo condition as a decrement, so the direction of change is obscured. No information was given about the reliability of the observer judgments. A strong trend towards impairment of performance, as defined by lower scores on judgment and concentration scales, was reported. There was no interaction between performance scores under marihuana and gender, driving experience or previous driving experience under marihuana.

A more recent study of automobile driving under marihuana on a closed course was performed by Attwood [1980]. Eight male subjects participated in the experiment at five sessions separated by 1-week intervals. The first session was a training session, and on the remaining four sessions the subjects received one of the following treatments:

(a) Placebo drink and placebo marihuana cigarette,

(b) alcohol producing 0.08% BAC plus a placebo cigarette,

(c) a placebo alcohol drink plus a marihuana cigarette containing 200 mcg/kg B.W. delta-9 THC, and

(d) alcohol producing 0.04% BAC plus marihuana containing 100 mcg delta-9 THC/kg B.W.

The experiment was performed on an airfield runway and involved five driving tasks:

(1) Accelerate to 60 kilometers per hour and maintain the vehicle for the length of the strip while keeping the same distance from the center line as normally would be done on the highway.

(2) Similar task except accelerate to 80 kilometers per hour maintaining that speed.

(3) Follow a lead car, which was varying speed, down the airstrip.

(4) Drive down the runway until a green light switches off and a red light comes on, at which point the subject was instructed to bring his car to a smooth stop. The light was switched at various distances of the subject and car from the light.

(5) The subject's car was following behind a lead car at 70 kilometers per hour while

another car was approaching in the other lane. Subjects were instructed to watch the oncoming car and decide when he was 14 seconds apart from the lead car, at which point they were instructed to pull out and pass the lead car as quickly and safely as possible.

The vehicle used in this study carried a complement of instrumentation capable of recording a variety of vehicle characteristics such as velocity, steering wheel position, lateral position, lateral acceleration, longitudinal acceleration and brake force. Various parameters of each of these measures were examined for each of the five tasks, and, finally, a multivariate analysis was performed integrating the information from all dependent variables. While the number of significant single variable comparisons was no more than would be expected by chance, the multivariate analysis was capable of distinguishing the four treatments from each other. The author concluded that vehicle handling was adversely affected by all of the drug conditions and that the different drug conditions affected different aspects of driving behavior.

With the exception of the initial pilot study, the experimental studies of the effects of marihuana on driving performance all suggest that car handling performance is impaired by marihuana. The emphasis in these studies, with the exception of Klonoff's examination of performance on the city streets, was upon car handling rather than the perceptual and cognitive aspects of safe driving, and, clearly, these were impaired, as shown by the objective measures. In a less clear way, there was a trend for the subjective measures of performance in the more complex city driving situation to appear impaired.

It should be noted that these studies, involving subjects under the influence of marihuana, tend to examine performance in less complex situations than are often met in real life driving situations. Resorting to the simplified demands of the closed course is necessary because of safety considerations. In real life driving situations the perceptual demands are considerably more complex. The suggestion from the Klonoff study is that these demands would face impairment of judgment and concentration. The conclusion of these studies is clearly that an impairment occurred, although it is premature to determine how these impairments of car performance as a whole relate to what we know about the behavioral effects of marihuana.

Interaction of marihuana and other drugs

With few exceptions, studies of the combined effect of marihuana with other drugs have selected alcohol as the companion drug. Epidemiological studies support the importance of examining this particular combination, as marihuana and alcohol have frequently been found jointly present in drivers.

Manno *et al.* [1971] examined 12 subjects receiving either 0, 5 or 10 mg of delta-9 THC, either alone or in combination with 0.52 gm alcohol/kg B.W. Behaviors studied included four levels of pursuit tracking and tests of paper and pencil mental tasks under the stress of delayed auditory feedback. The figures suggest that the alcohol which produced roughly 0.05% BAC had an additive increased impairment beyond that produced by marihuana.

Reid *et al.* [1973] examined compensatory tracking under the influence of 0, 21 and 88 mcg delta-9 THC/kg B.W. in combination with 0, 0.03% and 0.07% BAC. The data were analyzed by an application of human operator describing functions. The effect of alcohol was primarily to increase the time delay in responding to the tracking force functions changes. Marihuana appeared to increase random output. The effect of the combined dosages was to increase the number of statistically significant comparisons, but it was hard to assess the relative magnitude of the combined effect.

Chesher *et al.* [1976] examined 12 subjects on a battery of performance tests ranging from standing steadiness, simple and complex reaction time, manual dexterity, numerical reasoning and perceptual speed to a complex instrument known as the Vienna Determination Apparatus. Each subject received four treatments; placebo, alcohol alone, marihuana alone, and alcohol plus marihuana. The alcohol dose was 0.54 gm/kg B.W. The marihuana dose was 137 mcg THC/kg B.W. dissolved in sesame oil. The reaction time was insensitive as a measure, but standing steadiness, manual dexterity, perceptual speed and the Vienna Determination Apparatus did show impairment. The authors conclude that the increased impairment from the combination of the two drugs was at least an additive effect, a supposition supported by visual examination of the figures.

Macavoy and Marks [1975] examined four groups of eight subjects each. Each group of

eight subjects received one of the four alochol treatments, i.e. no drink, placebo drink, or sufficient alcohol to reach 0.05% or 0.10% BAC. Each subject returned on four occasions and had the four marihuana treatments, which were: (1) no marihuana cigarette, (2) a placebo marihuana cigarette, (3) 2.62 and 5.24 mcg delta-9 THC/kg B.W. The experimental task was a visual divided-attention test in which the subject has to detect the appearance of lights both in central and peripheral vision. Marihuana produced a highly significant impairment of performance, but the alcohol had no effect. The combined treatment had no greater effect than the marihuana alone. The authors note that marihuana was a within-subject treatment comparison, whereas the alcohol was a between-subject treatment, and added a note in proof in which they replicated this study using 12 subjects receiving nine treatment conditions; three alcohol levels times three marihuana levels, all within-subject. In the second experiment, both alcohol and cannabis produced significant impairments with the combined treatments being additive.

Chesher *et al.* [1976] examined 15 subject receiving 0.54 gm alcohol/kg B.W. and 214 mcg delta-9 THC/kg B.W., administered orally, both alone and in combination, as well as a placebo treatment on a battery of tests similar to that of Chesher *et al.* [1976] quoted above. The marihuana at this dose had a greater effect on the task than the alcohol, and the combined effects were additive, during the early testing period. However, at later testing periods the marihuana effects appeared to be more substantial than the marihuana and alcohol effects combined.

Sulkowski and Vachon [1977] compared alcohol and marihuana alone and in combination with dosages of 1 gm alcohol/kg B.W. and 18 mg delta-9 THC. They reported an increased incidence of nausea, vomiting and impairment of unspecified psychomotor tests for the combination.

Adams *et al.* [1978] examined the effects of the following treatments: placebo, 56 gm/kg alcohol, 8 and 15 mg delta-9 THC and .56 gm alcohol/kg B.W. combined with 15 mg THC. The response measure was the time course of glare recovery. Both marihuana and alcohol increased the recovery time in response to glare, with a greater impairment for the combined dosages.

Belgrave *et al.* [1979] examined the effects of 320 mcg/kg B.W. and delta-9 THC delivered orally in sesame oil, and 5.4 gm alcohol/kg B.W., both alone and in combination and in comparison with placebo upon a battery of performance tests similar to those used by Chesher *et al.* [1976]. Subjects were tested over a 5-hour period with an analysis performed by factor analysis of the combined performance score. Performance decrements due to alcohol for marihuana were noted on most of the factors, with the combined impairment extended through the 5-hour period.

Burns and Moskowtiz [1980] examined placebo and 0.58 gm alcohol/kg B.W. and 200 mcg delta-9 THC/kg B.W. alone and in combination on a battery of performance tests, including a compensatory tracking test, a divided-attention test, a rate of information processing test, a critical tracking task and a visual short-term memory test. As in the previous studies, the majority of tests found the combined degree to be clearly more impairing then either alone, with the results indicating an additive relationship.

This review of the literature on the combined effects of marihuana and alcohol indicates that the combined use produces an addition of the impairment induced by the two drugs, a matter of considerable social significance.

Additional issues

There are additional topics which bear discussing regarding psychomotor performance under marihuana:

1. Time estimation is a perceptual task which has been shown in many studies to be significantly impaired by marihuana. However, to conclude from that that this impairment would be a significant issue in situations such as driving is questionable. Speed is not estimated by dividing a distance estimate by a time estimate, rather it is a direct perceptual judgment. Neither in closed-course experiments nor in driving simulators have there been large changes in speed, although variability does change.

2. Another task shown to be sensitive to marihuana is the goal directed serial alternation

task. It has not been discussed here because, again, its relevance to man–machine interaction situations is not clear.

3. Short-term memory has also frequently been reported as significantly affected by marihuana. Again, it is not discussed here because its relevance to driving seems slight. In flying, recalling sequences of required behaviors is extremely important, but in driving the driver is responding primarily to the perceptual demands of the immediate situation.

CONCLUSIONS

It should be clear from the above review that there is more than sufficient experimental evidence to conclude that marihuana seriously impairs psychomotor performance required for driving. Among the areas which exhibited overwhelming evidence for impairment were:

A. Coordination as examined by hand steadiness, body sway and accuracy of execution of movement.

B. Tracking

C. Perception

D. Vigilance

E. Driving and flying performance measured by simulators.

F. Driving performance on the road.

Areas which show less reliable evidence of impairment or in which reliable evidence of small degree of impairment was found, included studies of reaction time, either simple or complex, studies of simple sensory functions and studies of ocular motor control functions. It should be noted that some reaction time studies, either simple or complex, do show considerable impairment under marihuana, but it is suggested that when this occurs there are other factors involved in the experiment besides the demand for rapid response, which are sensitive to the presence of marihuana and which are reflected in the speed of response. Clearly, marihuana is a substance which produces serious behavioral toxicological effects. Any situation in which safety both for self and others depends upon alertness and capability of control of man–machine interaction precludes the use of marihuana. This is not to suggest that marihuana is unusual in that respect. There are many other psychotropic substances such as alcohol or diazepam, to mention a few, which pose similar threats.

While some of the earlier studies in this field exhibited methodological problems, in defining dosage, or in drug administration or experimental design, the overwhelming majority are of more than satisfactory quality, and this is reflected in the general agreement among the experimental results. Essentially, there are no controversies about the experimental data which examine the issue of whether marihuana impairs psychomotor performance. There remain difficulties in determining from the magnitude and nature of psychomotor performance impairment due to marihuana the quantitative predictions about the increased probability of accidents in situations such as driving, flying, or industrial work. The social threat posed by any drug which impairs psychomotor performance is a function of the character of the population that uses it and the time and conditions under which it is used, e.g. how frequently it is used upon the road, and by what age group. These are all factors which interact with the pharmacological effect in determining the dangers to society associated with a given dose.

One major problem associated with these studies is the lack of clarity as to what behavioral faculties are the site of the impairment induced by marihuana. No effect of marihuana on any simple sensory input or motor output suffices to explain the distribution of areas of impairment reflected in these studies. It appears that some significant central behavioral area is impaired, but it is unclear what this is. It would certainly contribute to a better understanding of the pharmacological effects of marihuana and to a better assessment of the degree of resulting impairment if we had a better understanding of this site of impairment induced by marihuana.

A few limitations should be noted. These results are from studies administering up to 250 mcg/kg of delta-9 THC by cigarette smoking or roughly similar behavioral equivalent of orally ingested marihuana to subjects on the American scene. However, the delta-9 THC content of marihuana has recently been on a rapid increase, and from studies done of chronic users in other countries, it is clear that individuals can ingest 200 mg or higher quantities per day, acute dosages far in excess of those administered within the context of these existing studies. There-

fore, at some future time, studies involving larger acute doses to individuals with heavy chronic use might be necessary.

Also requiring further study is whether chronic marihuana users exhibit impairment even when they are not acutely intoxicated. This has not been examined at all.

REFERENCES

Adams A. J., Brown B., Flom M. C., Jones R. T. and Jampolsky A., Alcohol and marihuana effects of static visual acuity. *Am. J. Opt. Physiol. Opt.* **52**, 729–735, 1975.

Adams A. J., Brown B., Haegerstrom-Portnoy G., Flom M. C. and Jones R. T., Evidence for acute effects of alcohol and marihuana on color discrimination *Perception Psychophys.* **20**, 119–124, 1976.

Adams A. J., Brown B., Haegerstrom-Portnoy G., Flom M. C. and Jones R. T., Marijuana, alcohol, and combined drug effects on time course of glare recovery. *Psychopharmacology* **56**, 81–86, 1978.

Anonymous, Pilot study of marihuana effects is conducted. *Accid. Rep.*, February 1972.

Attwood D., Williams R., McBurney L. and Frecker R., Cannabis, alcohol and driving: Effects on selected closed-course tasks. In *Alcohol, Drugs and Traffic Safety, III* (Edited by L. Goldberg), pp. 938–953. Almqvist and Wiksell International, Stockholm, Sweden, 1981.

Baloh R. W., Sharma S., Moskowitz H. and Griffith R., Effect of alcohol and marihuana on eye movements. *Aviat. Space Environ. Med.* **50**, 18–23, 1979.

Bech P., Cannabis and alcohol: Effects on simulated driving. In *Biochemical and Pharmacological Aspects of Dependence and Reports on Marihuana Research* (Edited by H. M. Van Praag), pp. 160–163. De Erven, F. and Bohn, N.V., Haarlem, 1972.

Bech P., Christiansen J., Christrup H., Nyboe J., Rafaelsen L. and Rafaelsen O. J., Cannabis and alcohol effects on simulated car driving. *Science* **179**, 920–923, 1973.

Belgrave B. E., Bird K. D., Chesher G. B., Jackson D. M., Lubbe K. E., Starmer G. A. and Teo R. K. C., The effect of (-) trans-delta-9-tetrahydrocannabinol, alone and in combination with ethanol, on human performance. *Psychopharmacology* **62**, 53–60, 1979.

Borg J., Gershon S. and Albert M., Dose effects of smoked marijuana on human cognitive and motor functions. *Psychopharmacologia* **42**, 211–218, 1975

Borkenstein R. F., Crowther R. F., Shumate R. P., Ziel W. B. and Zylman R., *The Role of the Drinking Driver in Traffic Accidents*. Department of Police Administration, Indiana University, Bloomington, 1967.

Burns M. and Moskowitz H., Alcohol, marihuana and skills performance. In *Alcohol, Drugs and Traffic Safety, III* (Edited by L. Goldberg), pp. 954–968., Almqvist and Wiksell International, Stockholm, Sweden, 1981.

Caldwell D. F., Myers S. A. and Domino E. F., Effects of marihuana smoking on sensory thresholds in man. *Chem. Abst.* **72**, 109749, 1970.

Caldwell D. F., Myers S. A., Domino E. F. and Mirriam P. E., Auditory and visual threshold effects of marihuana in man. *Perceptual Motor Skills* **29**, 755–759, 1969.

Casswell S. and Marks D., Cannabis induced impairment of performance of a divided attention task. *Nature* **241**, 60–61, 1973.

Chesher G. V., Franks H. M., Hensley V. R., Hensley W. J., Jackson D. M., Starmer G. A. and Teo R. K. C., The interaction of ethanol and delta-9-tetrahydrocannabinol in man, effects of perceptual, cognitive and motor functions. *Med. J. Austral.* **2**, 159–163, 1976.

Cimbura G., Warren R. A., Bennett R. C., Lucas D. M. and Simpson H. M., Drugs detected in fatally injured drivers and pedestrians in the Province of Ontario. Traffic Injury Research Foundation of Canada, Ottawa, 1980.

Clark L. D., Hughes R. and Nakashima E. F., Behavioral effects of marihuana: Experimental studies. *Arch. Gen. Psychiatry* **23**, 193–198, 1970.

Clark L. D. and Nakashima E. N., Experimental studies of marihuana. *Am. J. Psychiatry* **125**, 379–384, 1968.

Crancer A. J. and Quiring D. L., Driving records of persons arrested for illegal drug use. Department of Motor Vehicles, State of Washington, 1968.

Crancer A. J., Dille J. M., Delay J. C., Wallace J. E. and Hakin M., Comparison of the effects of marihuana and alcohol on simulated driving performance. *Science* **164**, 851–854, 1969.

Dornbush R. L., Fink M. and Freedman A. M., Marijuana, memory, and perception. *Am. J. Psychiatry* **128**, 194–197, 1971.

Dott A. B., Effect of marihuana on risk acceptance in a simulated passing task. Public Health Service Report ICRL-RR-71-3, DHEW Publication No. HSM-72-10010, Washington, DC, 1972.

Ellingstad V. S., McFarling L. H. and Struckman D. L., Alcohol, marihuana and risk taking. Vermillion Human Factors Laboratory, South Dakota University, 1973.

Evans M. A., Martz R. and Brown D. J., Impairment of performance with low doses of marihuana. *Clin. Pharmacol. Therapeut.* **14**, 936–940, 1973.

Hansteen R. W., Miller R. D. and Lonero L., Effects of cannabis and alcohol on automobile driving and psychomotor tracking. *Ann. N.Y. Acad. Sci.* **282**, 240–256, 1976.

Hill S. Y., Schwin R., Goodwin D. W. and Powell B. J., Marihuana and pain. *J. Pharmacol. Exper. Therapeut.* **188**, 415–418, 1974.

Janowsky D. S., Marijuana effects on simulated flying ability. *Am. J. Psychiatry* **133**(4), 384–388, 1976.

Janowsky D. S., Meacham M. P., Blaine J. D., Schoor M. and Bozzetti L. P., Simulated flying performance after marihuana intoxication. *Aviat. Space Environ. Med.* **47**, 124–128, 1976.

Jones R. T., Marihuana induced "high": Influence of expectation, setting and previous drug experience. *Pharmacol. Rev.* **23**, 359–369, 1971.

Jones R. T. and Stone G. C., Psychological studies of marihuana and alcohol in man. *Psychopharmacologia* **18**, 108–117, 1970.

Kalant H., Marihuana and simulated driving. *Science* **166**, 640, 1969.

Kiplinger G. F., Manno J. E. and Rodda B. G., Dose response analysis of the effects of tetrahydrocannabinol in man. *Clin. Pharmacol. Therapeut.* **12**, 650–657, 1971.

Klonoff H., Marijuana and driving in real-life situations. *Science* **186**, 317–324, 1974.

Kvalseth T. O., Effects of marihuana on human reaction time and motor control. *Perceptual Motor Skills* **45**, 935–939, 1977.

Macavoy M. G. and Marks D. F., Divided attention performance of cannabis users and non-users following cannabis and alcohol. *Psychopharmacologia* **44**, 147–152, 1975.

Manno J. E., Kiplinger G. F., Scholz N. and Forney R. B., The influence of alcohol and marihuana on motor and mental performance. *Clin. Pharmacol. Therapeut.* **12**, 202–211, 1971.

Mayor's Committee on Marihuana, *The Marihuana Problem in the City of New York*. Jacques Cattell Cattell Press, Lancaster, PA. 1944 (the LaGuardia report).

McBay A. J. and Owens S. M., Marihuana and driving. In *Problems of Drug Dependence*, 1980 *NIDA Research Monograph No.* 34 (Edited by L. S. Harris), pp. 257–263. National Institute on Drug Abuse, Rockville, MD, 1981.

Milstein S. L., MacCannell K., Karr G. and Clark S., Marijuana-produced impairments in coordination. *J. Nervous Mental Dis.* **161**, 26–31, 1975.

Moskowitz H., Sharma S. and McGlothlin W., The effects of marihuana upon peripheral vision as a function of the information processing demands upon central vision. *Perceptual Motor Skills* **35**, 875–882, 1972.

Moskowitz H., Sharma S. and Schapero M., A comparison of the effects of marihuana and alcohol on visual functions. In *Current Research on Marihuana* (Edited by M. I. Lewis), pp. 129–150. Academic Press, New York, 1972.

Moskowitz H., McGlothlin W. and Hulbert S., The effect of marihuana dosage in driver performance. Institute of Transportation and Traffic Engineering Report UCLA-ENG-7341, University of California at Los Angeles, CA, 1973.

Moskowitz H. and McGlothlin W., Effects of marihuana on auditory signal detection. *Psychopharmacologia* **40**, 137–145, 1974.

Moskowitz H., Shea R. and Burns M., Effect of marihuana on the psychological refractory period. *Perceptual Motor Skills* **38**, 959–962, 1974.

Moskowitz H., Ziedman K. and Sharma S., Visual search behavior while viewing driving scenes under the influence of alcohol and marihuana. *Human Factors* **18**, 417–432, 1976.

Moskowitz H., Hulbert S. and McGlothlin W., Marihuana: Effects on simulated driving performance. *Accid. Anal. & Prev.* **8**, 45–50, 1976.

Moskowitz H. and Sharma S., The effects of marihuana on skills performance. Report to the National Institute on Drug Abuse, Contract No. 271-76-3316, Southern California Research Institute, Los Angeles, CA, 1979.

Moskowitz H., Sharma S. and Zieman K., Duration of skills performance impairment. In *Proceedings of the 25th Conference of the American Association for Automotive Medicine*, pp. 87–96. San Francisco, CA 1981.

Nichols J. L., Drug use in highway safety: A review of the literature. Report No. DOT-HS-800-580, National Highway Traffic Safety Administration, Department of Transportation, Washington, DC, 1971.

Peeke S. C., Jones R. T. and Stone G. C., Effects of practice on marihuana-induced changes in reaction time. *Psychopharmacology* **48**, 159–163, 1976.

Peters B., Lewis E. G., Dustman R. E., Straight R. C. and Beke E. C., Sensory perceptual, motor and cognitive functioning and subjective reports following oral administration of delta-tetrahydrocannabinol. *Psychopharmacology* **47**, 141–148, 1976.

Rafaelsen L., Christup H. and Bech P., Effects of cannabis and alcohol on psychological tests. *Nature* **242**, 117–118, 1973.

Reeve V. C., Incidents of marihuana in a California impaired driver population. California State Department of Justice, Sacramento, CA, 1979.

Reid L. D., Ibrahim M. K. F., Miller R. D. and Hansteen H. W., The influence of alcohol and marihuana on a manual tracking task. Technical Paper No. 730092, Society of Automotive Engineers Congress, Detroit, Michigan, 1973.

Rossi A. M., Kuehnle J. C. and Mendelson J. H., Effects of marijuana on reaction time and short term memory in human volunteers. *Pharmacol. Biochem. Behavior* **6**(1), 73–77, 1977.

Roth W. T., Tinklenberg J. R., Whitaker C. A., Darley C. F., Kopell B. S. and Hollister L. E., The effect of marihuana on tracking task performance. *Psychopharmacology* **33**, 259–265, 1973.

Salvendy G. and McCabe G. P., Marijuana and human performance. *Human Factors* **17**, 229–235, 1975.

Schaefer C. F., Gunn C. G. and Dubowski K. M., Dose-related heart-rate, perceptual and decisional changes in man following marijuana smoking. *Perceptual Motor Skills* **44**, 3–16, 1977.

Schwin R., Hill S. Y., Goodwin D. W. and Powell B., Marihuana and critical flicker fusion. *J. Nervous Mental Dis.* **158**, 142–144, 1974.

Sharma S. and Moskowitz H., Effect of marihuana on the visual autokinetic phenomenon. *Perceptual Motor Skills* **35**, 891–894, 1972.

Sharma S. and Moskowitz H., Effects of two levels of attention demand on vigilance performance under marihuana. *Perceptual Motor Skills* **38**, 967–970, 1974.

Sharma S. and Moskowitz H., Marihuana dose study of vigilance performance. In *Proceedings*, 81*st Annual Conference*, *American Psychological Association*, pp. 1035–1036, 1973.

Sharma S. and Moskowitz H., Marihuana effects on a critical tracking task. In *Proceedings of the 19th Conference of the American Association for Automotive Medicine*, pp. 285–291, 1975.

Smart R. B., Marihuana and driving risk among college students. *J. Safety Res.* **6**, 155–158, 1974.

Smiley A. M., Moskowitz H. and Ziedman K., Driving simulator studies of marihuana alone and in combination with alcohol. In *Proceedings of the 25th Conference of the American Association for Automotive Medicine*, pp. 107–116. San Francisco, CA, 1981.

Stillman R. C., Wolkowitz O., Weingartner H., Waldman I., DeRenzo E. V. and Wyatt R. J., Marijuana: Differential effects on right and left hemisphere functions in man. *Life Sci.* **21**, 1793–1800, 1977.

Sulkowski A. and Vachon L., Side effects of simultaneous alcohol and marijuana use. *Am. J. Psychiatry* **134**, 691–692, 1977.

Sulkowski A., Vachon L. and Rich E. S., Propranolol effects on acute marijuana intoxication in man. *Psychopharmacology* **52**, 47–53, 1977.

Teale J. D., Clough J. M., King L. J., Marks V., Williams P. L. and Moffat A. C., The incidence of cannabinoids in fatally injured drivers: An investigation by radioimmunoassay and high pressure liquid chromatography. *J. Forensic Sci. Soc.* **17**, 177–183, 1977.

Thaler S., Fass P. and Fitzpatrick D., Marihuana and hearing. *Can. J. Otholaryngol.*, 291–295, 1973.

Waller J. A., Lamborn K. P. and Steffhagen R. A., Marihuana and driving among teenagers: Reported use patterns, effects and experiences related to driving. *Accid. Anal. & Prev.* **6**, 141–161, 1974.

Warren R. A. and Simpson H. M., Cannabis and Driving: Implications of moderation in penalties. Traffic Injury Research Foundation of Canada, Ottawa, 1980.

Warren R., Simpson H., Hilchie J., Cimbura G., Lucas D. and Bennett R., Drugs detected in fatally injured drivers in the Province of Ontario. In *Alcohol, Drugs and Traffic Safety* (Edited by L. Goldberg), pp. 203–217. Almqvist and Wiksell International, Stockholm, Sweden, 1981.

Weil A. T., Zinberg N. E. and Nelsen J. M., Clinical and psychological effects of marijuana in man. *Science* **162**, 1234, 1968.