HUMAN PSYCHOPHARMACOLOGY
Hum. Psychopharmacol. Clin. Exp. **13**, S70–S78 (1998)

Marijuana's Impairing Effects on Driving are Moderate When Taken Alone But Severe When Combined with Alcohol

H. ROBBE
Maastricht University, Maastricht, The Netherlands.
Presently at: Bakken Research Center, P.O. Box 1220, 6201 MP Maastricht, The Netherlands.

Previous experimental and epidemiological studies failed to provide unequivocal evidence that marijuana, either alone or in combination with alcohol, impairs a driver's performance to the extent that it will compromise traffic safety. We investigated the effects of marijuana, alone and in combination with alcohol, on actual driving in four, single-blind, randomized, cross-over studies. In Study 1, 24 subjects performed a road-tracking test on a closed segment of a primary highway after smoking marijuana that contained 0, 100, 200 and 300 μg/kg Δ^9-tetrahydrocannabinol (THC). In Study 2, 16 new subjects smoked the same THC doses before they performed a road-tracking and a car-following test; however, this time in the presence of other traffic. In Study 3, two groups of 16 subjects performed a city driving test. One group smoked marijuana delivering 0 and 100 μg/kg THC prior to driving; the other group drunk orange juice mixed with or without a low dose of alcohol. In Study 4, 18 subjects performed a road-tracking and a car-following test in each of six conditions where they smoked marijuana with 0, 100, or 200 μg/kg THC after they had consumed orange juice with or without alcohol. In these studies, marijuana alone significantly increased lateral position variability in the road-tracking test and distance variability during deceleration manoeuvres in the car-following test. Reaction times during car-following were not significantly affected, and a THC dose of 100 μg/kg did not impair city driving performance. Blood plasma concentrations of THC and THC-COOH were not related to the degree of impairment. A low dose of alcohol (i.e. blood alcohol concentrations around 0·04%) impaired performance in all driving tests. Whereas marijuana's effects on driving performance were small (100 μg/kg THC) or moderate (200 and 300 μg/kg) when taken alone, they were severe when combined with a low dose of alcohol. In conclusion, marijuana alone impairs driving performance, with the degree of impairment increasing from small to moderate as the THC dose increases from 100 to 300 μg/kg. However, when low to moderate doses of THC (100 and 200 μg/kg) are taken in combination with a low dose of alcohol sufficient for attaining a BAC of about 0·04% actual driving is severely impaired. © 1998 John Wiley & Sons, Ltd.

KEY WORDS — marijuana; cannabis; alcohol; driving performance; impairment

INTRODUCTION

The effects of marijuana on driving performance and traffic safety have been explored both by epidemiological and experimental research. A review of these studies have been published elsewhere (Robbe and O'Hanlon, 1993; Robbe, 1994), but the major conclusions will be repeated here.

Although epidemiological research has shown that some people do drive after cannabis use and that drivers involved in accidents often show the drug's presence, marijuana's causal role still remains obscure due to the high proportion of drivers who also used alcohol and the lack of proper control groups. Laboratory studies of the effects of Δ-9-tetrahydrocannabinol (THC), marijuana's primary active constituent, on driving-related skills such as tracking, divided attention, and vigilance, have repeatedly shown performance impairment occurring after inhaled doses as low as about 40 μg/kg. Yet more realistic tests in driving simulators and on closed courses indicated that THC in single inhaled doses up to 250 μg/kg has relatively minor effects on driving performance, certainly less than blood alcohol concentrations (BACs) in the range 0·08–0·10%.

A similar disparity between studies appears when one reviews the literature on the effects of the combination of marijuana and alcohol (Robbe and O'Hanlon, in press). The latest and largest epidemiological study by Terhune (1992) shows that the combination of marijuana and alcohol is over-represented in injured and dead drivers and

CCC 0885–6222/98/S20070–09$17·50

more so in those who actually caused the accidents to occur. Terhune's study suggests that the drugs interact synergistically (i.e. multiplicatively) to cause gross behavioural impairment responsible for the users' crashes. However, these results are not corroborated by experimental studies in laboratories, driving simulators or actual driving on a closed road. In general, these studies have shown little or no effects of marijuana alone with THC doses up to about 250 μg/kg, little or no effect of alcohol in BACs up to 0·10%, and nothing more than an additive effect of the two drugs in combination.

Thus epidemiological and experimental research have not provided unequivocal evidence that marijuana, either alone or in combination with alcohol, impairs a driver's performance to the extent that it will compromise traffic safety. Therefore a research program was initiated to assess the effects of marijuana and alcohol, alone and in combination, on actual driving in a real environment, i.e. in actual traffic. Only one study has been conducted in actual traffic before this program started (Klonoff, 1974). The driving examiners in that study rated the drivers' performance as significantly worse on scales of judgement and concentration, but the validity of the method used by Klonoff was later questioned by Moskowitz (1985) and Smiley (1986).

Our research program consisted of four driving studies in which a variety of driving tasks were employed, including: maintenance of a constant speed and lateral position during uninterrupted highway travel, following a leading car with varying speed on a highway, and city driving. In order to determine the highest THC dose to be administered in the driving studies, a pilot study preceded the driving studies for identifying the THC dose that current users of marijuana smoke to achieve their usual 'high'.

The first driving study was conducted on a closed segment of a primary highway. The subjects' road-tracking performance was measured after smoking placebo marijuana and active marijuana with three different THC doses. In the second study the same THC doses were administered, but this time subjects drove on a highway in the presence of other traffic. Moreover, two driving tests were employed: a road-tracking and a car-following test. In the third study, the subjects' performance was assessed while driving in the city of Maastricht. One group of subjects performed the test after smoking active and placebo marijuana, while another group of subjects performed the same test after drinking a low dose of alcohol and placebo alcohol. The program was concluded with a study that explored the interaction between marijuana and alcohol. Subjects performed the road-tracking and car-following tests, in the presence of other traffic, while under the influence of one of three THC doses and one of two ethanol doses. Together these studies should provide a better insight into marijuana's effects on real-world driving, both when taken alone and when taken in combination with alcohol.

GENERAL PROCEDURES

Subjects in all studies were so-called recreational users of marijuana or hashish, i.e. they smoked the drug more than once a month, but not daily. Subjects who were administered ethanol used that drug at least once a week, but not daily. They were all healthy, between 21 and 40 years of age, had normal weight and binocular acuity, and were licensed to drive an automobile. They were informed about the nature of the study and gave informed consent in writing prior to their participation. Furthermore, law enforcement authorities were contacted, with the volunteers' consent, to verify that they had no previous arrests or convictions for drunken driving or drug trafficking.

Each subject was required to submit a urine sample immediately upon arrival at the test site. Samples were assayed qualitatively for the following common 'street drugs' (or metabolites): cannabinoids, benzodiazepines, opiates, cocaine, amphetamines and barbiturates. In addition, a breath sample was analyzed for the presence of alcohol. In Studies 1–3 blood samples were repeatedly taken after smoking by venepuncture. Quantitative analysis of THC and THC-COOH in plasma was performed by gas chromatography/mass spectrometry (GC/MS) using deuterated cannabinoids as internal standards.

Marijuana and placebo marijuana cigarettes were supplied by the US National Institute on Drug Abuse (NIDA). The lowest and highest THC concentrations in the marijuana cigarettes used in the studies were 1·75% and 3·95%, respectively. Cigarettes were cut to provide lengths appropriate for the subjects' weight. Placebo cigarettes were similarly shortened. All were humidified before the subjects smoked them as completely as possible through a plastic holder in their customary fashion.

Subjects were accompanied during every driving test by a licensed driving instructor. A redundant control system in the test vehicle was available for controlling the car, should emergency situations arise.

In driving studies 1–3, subjects repeatedly performed certain simple laboratory tests (e.g. critical instability tracking, hand and posture stability), estimated their levels of intoxication and indicated their willingness to drive under several specified conditions of urgency. In addition, heart rate and blood pressure were measured. Results of these measurements are reported elsewhere (Robbe, 1994; Robbe and O'Hanlon, 1993).

PILOT STUDY

Methods

Twenty-four subjects, equally comprised of men and women, were allowed to smoke part or all of three marijuana cigarettes within 15 min until achieving their desired psychological effect. Cigarettes weighted 767 mg on average and contained 2·57% or about 20 mg THC. When subjects voluntarily stopped smoking, cigarettes were carefully extinguished and retained for subsequent gravimetric estimation of the consumed amount.

Results

Six subjects consumed one cigarette, 13 smoked two and four smoked three (data from one male subject were excluded from the results because no drug was found in his plasma after smoking). On average subjects consumed 20·8 mg THC which was the equivalent of 308 μg/kg body weight. It should be noted that these amounts of THC represent both the inhaled dose and the portion that was lost through pyrolysis and side-stream smoke during the smoking process. There were no significant differences between males and females, nor between frequent and infrequent users with respect to the weight adjusted preferred dose.

STUDY 1: MARIJUANA AND DRIVING ON A RESTRICTED HIGHWAY

Methods

The first driving study was conducted on a highway closed to other traffic. The same 12 men and 12 women who participated in the pilot study served again as the subjects. They were treated on separate occasions with marijuana cigarettes containing THC doses of 0 (placebo), 100, 200, and 300 μg/kg. Marijuana cigarettes were prepared from batches containing 1·75% THC for the two lowest, and 2·57% THC for the highest dose. Treatments were administered double-blind and in a counterbalanced order. On each occasion, subjects performed a 22-km road-tracking test beginning 40 min after initiation of smoking and repeated 1 h later. The test involved maintaining a constant speed at 90 km/h and a steady lateral position between the delineated boundaries of the traffic lane. The primary dependent variable was the standard deviation of lateral position (SDLP), which has been shown to be both highly reliable and very sensitive to the influence of sedative medicinal drugs and alcohol. Other measurements included mean lateral position, and mean and standard deviation of speed. Blood samples were taken 10 min before the driving tests (i.e. 30 and 90 min after initiation of smoking, respectively).

Results

All subjects were willing and able to finish the driving tests without great difficulty. Data from one male subject, the same as in the previous study, were excluded from the results because no drug was found in his plasma after smoking.

Figure 1 demonstrates that marijuana impairs driving performance as measured by an increase in lateral position variability: all three THC doses significantly affected SDLP relative to placebo ($p < 0{\cdot}012$, 0·001 and 0·001, for the 100, 200 and 300 μg/kg conditions, respectively). The *dose by*

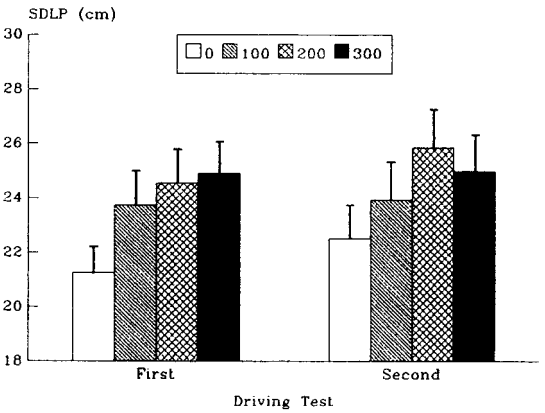

Figure 1. Mean (±SE) SDLP by dose and time

time effect was not significant, indicating that impairment after marijuana was the same in both repetitions of the test. Marijuana's effects on SDLP were compared to those of alcohol obtained in a very similar study by Louwerens *et al.* (1987). It appeared that the effects of the various administered THC doses (100–300 μg/kg) on SDLP were equivalent to those associated with BACs in the range of 0·03–0·07%. Other driving performance measures were not significantly affected by THC. Plasma concentrations of the drug were clearly related to the administered dose and time of blood sampling, but unrelated to driving performance impairment.

STUDY 2: MARIJUANA AND DRIVING ON A NORMAL HIGHWAY

Methods

The second driving study was conducted on a highway in the presence of other traffic and involved both a road-tracking and a car-following test. A new group of 16 subjects, equally comprised of men and women, participated in this study. A conservative approach was chosen in designing the study in order to satisfy the strictest safety requirements. That is, the study was conducted according to an ascending dose series design where both active drug and placebo conditions were administered, double-blind, at each of three THC dose levels. THC doses were the same as those used in the previous study, namely 100, 200, and 300 μg/kg. Marijuana cigarettes were prepared from batches containing 1·77% THC for the lowest, 2·64% THC for the intermediate, and 3·58% THC for the highest dose. Corresponding placebo cigarettes were shortened to the same length. If any subject would have reacted in an unacceptable manner to a lower dose, he/she would not have been permitted to receive a higher dose.

The subjects began the car-following test 45 min after smoking. The test was performed on a 16-km segment of the highway and lasted about 15 min. After the conclusion of this test, subjects performed a 64-km road-tracking test on the same highway which lasted about 50 min. At the conclusion of this test, they participated again in the car-following test. Blood samples were taken both before the first and after the last driving test (i.e. 35 and 190 min after initiation of smoking, respectively).

The road-tracking test was the same as in the previous study, except for its duration and the presence of other traffic. The car-following test involved attempting to match velocity with, and maintain a constant distance from, a preceding vehicle as it executed a series of deceleration/acceleration manoeuvres. The preceding vehicle's speed would vary between 80 and 100 km/h and the subject was instructed to maintain a 50 m distance however the preceding vehicle's speed might vary. The duration of one deceleration and acceleration manoeuvre was approximately 50 s and six to eight of these manoeuvres were executed during one test, depending upon traffic density. The subject's average reaction time to the movements of the preceding vehicle was the primary dependent variable; other variables included mean and standard deviation of distance during manoeuvres.

Results

All subjects were able to complete the series without suffering any untoward reaction while driving. Data from one female subject were excluded from the results because no drug was found in her plasma after smoking.

Road-tracking performance in the standard test was impaired in a dose-related manner by THC and confirmed the results obtained in the previous study (Figure 2). The 100 μg/kg dose produced a slight elevation in mean SDLP, albeit not statistically significant ($p < 0·13$). The 200 μg/kg dose produced a significant ($p < 0·023$) elevation, of dubious practical relevance. The 300 μg/kg dose produced a highly significant ($p < 0·007$) elevation which may be viewed as practically relevant. After

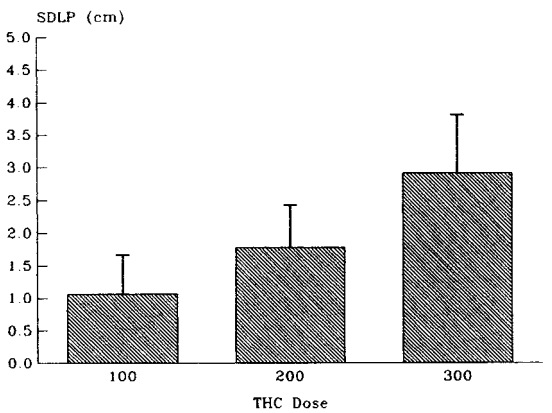

Figure 2. Mean changes (±SED) in SDLP in the road-tracking test by THC dose, relative to placebo

marijuana smoking, subjects drove with an average speed that was only slightly lower than after placebo and very close to the prescribed level.

In the car-following test, subjects maintained a distance of 45–50 m while driving in the successive placebo conditions. They lengthened mean distance by 8, 6 and 2 m in the corresponding THC conditions after 100, 200 and 300 μg/kg, respectively. The initially large drug–placebo difference and its subsequent decline is a surprising result. It seems that the subjects' caution was greatest the first time they undertook the test under the influence of THC (which was in this study always the lowest THC dose) and progressively less thereafter. Reaction times varied in a similar manner between conditions as mean distance; both variables were highly interrelated: $r = 0{\cdot}76$, across all conditions. Therefore reaction times were analyzed by means of covariance analysis with distance as the covariate. The changes in these 'adjusted' reaction times are shown in Figure 3. Though each THC dose increased reaction time compared to placebo, none of the changes were statistically significant.

As in the previous study, plasma concentrations of the drug were not related to driving impairment.

STUDY 3: MARIJUANA VERSUS ALCOHOL DURING CITY DRIVING

Methods

The objective of the study was to assess if a THC dose that had only a slight effect on highway driving would have a larger and significant effect on driving in a more complex environment, i.e. in urban traffic. For this and safety reasons the THC dose in this study was restricted to 100 μg/kg. It was given to a new group of 16 regular marijuana (or hashish) users, along with a placebo. For comparative purposes, another group of 16 regular users of alcohol, but not marijuana, were treated with a modest dose of their preferred recreational drug, alcohol, and again placebo, before undertaking the same city driving test. Both groups were equally comprised of men and women.

Marijuana was administered to deliver 100 μg/kg THC. The driving test commenced 30 min after smoking. The alcohol dose was chosen to yield a BAC approaching 0·05% when the driving test commenced 45 min after onset of drinking. Active drug and placebo conditions were administered double-blind and in a counterbalanced order in each group. Blood samples were taken immediately prior to and following all placebo and drug driving tests (i.e. 20 and 80 min after initiation of smoking, and 35 and 95 min after initiation of drinking).

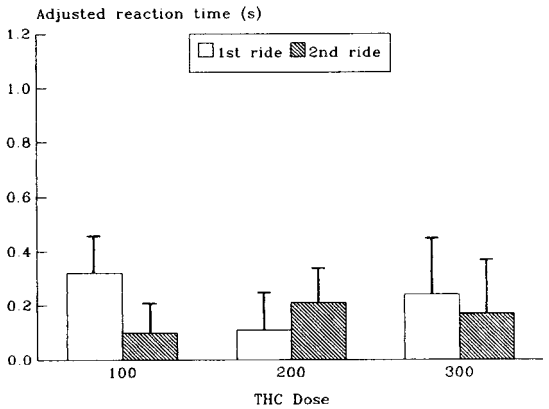

Figure 3. Mean changes (±SED) in 'adjusted' reaction time by THC dose, relative to placebo

Driving tests were conducted in daylight over a constant 17·5-km route within the city limits of Maastricht. Subjects drove their placebo and active-drug rides through heavy, medium and low density traffic on the same day of the week, and at the same time of day. Two scoring methods were employed in the present study. The first, a 'molecular' approach adopted from Jones (1978), involved the employment of a specially trained observer who applied simple and strict criteria for recording when the driver made or failed to make each in a series of observable responses at predetermined points along a chosen route. The second, a 'molar' approach, required the driving instructor acting as the safety controller during the tests to retrospectively rate the driver's performance using a shortened version of the Royal Dutch Tourist Association's Driving Proficiency Test. In total 108 items were dichotomously scored as either pass or fail. Total test performance was measured by the percentage items scored as 'pass'. Subscores were calculated for vehicle checks, vehicle handling, traffic manoeuvres, observation and understanding of traffic, and turning. This method has been applied previously to show the impairing effects of alcohol and diazepam (De Gier, 1979; De Gier *et al.*, 1981).

Results

Data from two male subjects in the marijuana group were excluded from the results because

Table 1. Mean (±SED) changes in driving performance scores measured by the molar approach for the marijuana ($N = 14$) and alcohol ($N = 16$) group and the significance of each change and difference between changes

Dependent variable	Marijuana group		Alcohol group		Marijuana vs alcohol
	Δ	$p <$	Δ	$p <$	$p <$
Total score	−0·7 (±2·7)	NS	−6·8 (±1·8)	0·002	0·065
Vehicle checks	−0·6 (±1·5)	NS	+0·5 (±1·3)	NS	NS
Vehicle handling	+3·7 (±2·8)	NS	−8·4 (±2·2)	0·002	0·002
Traffic manoeuvres	−2·7 (±3·1)	NS	−8·4 (±2·3)	0·003	NS
Observation and understanding of traffic	+1·8 (±8·7)	NS	−6·3 (±7·0)	NS	NS
Turning	−1·8 (±4·9)	NS	+3·1 (±7·5)	NS	NS

neither THC nor THC-COOH was found in their plasma after smoking.

Neither alcohol nor marijuana significantly affected driving performance measures obtained by the molecular approach, indicating that it may be relatively insensitive to drug-induced changes. The molar approach was more sensitive. Table 1 shows that a modest dose of alcohol (mean BAC 0·034%) produced a significant impairment in city driving, relative to placebo. More specifically, alcohol impaired both vehicle handling and traffic manoeuvres. Marijuana, administered in a dose of 100 μg/kg THC, on the other hand, did not significantly change mean driving performance as measured by this approach.

Subjects' self-ratings of driving quality and effort to accomplish the task were strikingly different from the driving instructor's ratings. Both subject groups rated their driving performance following placebo as somewhat better than 'normal'. Following the active drug, self-ratings were 35% lower in the marijuana group ($p < 0·009$) but only 5% in the alcohol group (NS). Perceived effort to accomplish the driving test was about the same in both groups following placebo. Following the active drug, a significant increase in perceived effort was reported by the marijuana ($p < 0·04$), but not the alcohol group.

Thus, there is evidence that subjects in the marijuana group were not only aware of their intoxicated condition, but were also attempting to compensate for it. These seem to be important findings. They support both the common belief that drivers become overconfident after drinking alcohol and investigators' suspicions that they become more cautious and self-critical after consuming small amounts of marijuana.

Drug plasma concentrations were neither related to absolute driving performance scores nor to the changes that occurred from placebo to drug conditions. With respect to THC, these results confirm the findings in previous studies. They are somewhat surprising for alcohol, but may be due to the restricted range of ethanol concentrations in the plasma of different subjects.

STUDY 4: MARIJUANA COMBINED WITH ALCOHOL DURING HIGHWAY DRIVING

Methods

As Study 2, this study was conducted on a highway in the presence of other traffic and involved both the road-tracking and the car-following test. Eighteen volunteer subjects, comprised of men and women in equal proportions, were treated with drugs and placebo according to a balanced, 6-way, observer- and subject-blind, cross-over design. On separate evenings they were given weight-calibrated doses of THC and alcohol, or placebos for one or both substances as follows: alcohol placebo + THC placebo; alcohol placebo + THC 100 μg/kg; alcohol placebo + THC 200 μg/kg; alcohol + THC placebo; alcohol + THC 100 μg/kg; and alcohol + THC 200 μg/kg. The initial alcohol dose was sufficient for achieving a peak blood concentration (BAC) of about 0·07%. Booster doses were later given to sustain BAC around 0·04% during testing. Initial drinking preceded smoking by 60 min. Driving tests began 30 min after smoking at 21:00 h. Subjects undertook them in pairs on the same evening. One started with the car-following test and the other 4 min later with the road-tracking test. After driving a distance of

40 km on the highway (lasting about 25 min), the first subject drove off and awaited the second. When he/she arrived, the pair exchanged roles, returned to the highway, and drove in the reverse direction until returning to the origin where both paused for 15 min. A second booster dose of alcohol was then administered to subjects with BACs below 0·05%. Beginning around 22:15 h, the subjects drove through another circuit while repeating the same series of tests as before. Testing concluded at approximately 23:15 h.

The road-tracking test, was with the exception of its length, the same as in Study 2, the primary variable being SDLP. The car-following test was slightly modified: previously, the investigator in the preceding car started deceleration manoeuvres immediately after the completion of an acceleration manoeuvre, in a non-standardized manner, and both were performed within 50 s. This time, the investigator initiated each manoeuvre by activating a microprocessor-driven cruise-control. The vehicle's speed then rose or fell in a constant manner until arriving at a point 15 km/h higher or lower than where it began. The investigator drove at the newly established speed for 0·5–5·0 min before initiating the next manoeuvre. About eight manoeuvres in each direction were accomplished over both repetitions of the test. Average RT and the standard deviation of distance for acceleration and deceleration manoeuvres, separately, were the major dependent variables.

Results

On average subjects consumed 64 ml ethanol mixed with orange juice before marijuana smoking, and 10 ml halfway through the tests. Mean BACs were very similar between conditions in which alcohol was administered, and most of the subjects performed the tests while their BACs fluctuated around 0·04% in a generally declining trend from 0·05% to 0·035%.

Multivariate analyses revealed significant main effects of alcohol ($p < 0{\cdot}001$) and THC ($p < 0{\cdot}001$) but no significant interaction. The interaction with repetitions of the test were not significant, therefore Figure 4 displays data averaged across repetitions. Univariate analyses showed that compared to double placebo all drug combinations increased mean SDLP significantly. The magnitude of the mean effects were minor after alcohol alone and THC 100 μg/kg alone, moderate after THC 200 μg/kg alone, and severe after both THC doses in combination with alcohol. The mean changes in the latter conditions were evaluated relative to a previously established alcohol calibration curve (Louwerens *et al*, 1987): the combination of alcohol and THC 100 μg/kg produced a rise in mean SDLP the equivalent of that associated with BAC = 0·09%, and the combination of alcohol and THC 200 μg/kg produced an effect equivalent to that associated with BAC = 0·14%.

In 25 of 216 car-following tests no, or only very few, data were obtained which was mainly due to the subjects' unwillingness or inability to consistently maintain a following distance within the range of the sensor/transmitter system. Therefore, planned multivariate analyses could not be applied to these data. Instead, data were combined across test repetitions within each condition to yield average parameter values that were analyzed by paired *t*-tests for making separate comparisons between double placebo and every drug condition.

Mean RT during deceleration manoeuvres varied across treatment conditions from 4·65 s at the placebo level to 6·33 s (+36%) under the combined influence of alcohol and THC 200 μg/kg. It was only in the latter condition, however, that the change was statistically significant ($p < 0{\cdot}009$). Headway variability (H_{SD}) varied from 5·69 to 7·78 m (+37%) across conditions in a similar manner as mean RT, but now all changes compared to double placebo were significant.

The subjects' and instructors' rating of the formers' driving quality clearly reflected the adverse objective effects of alcohol and THC alone and in combination. In addition, the

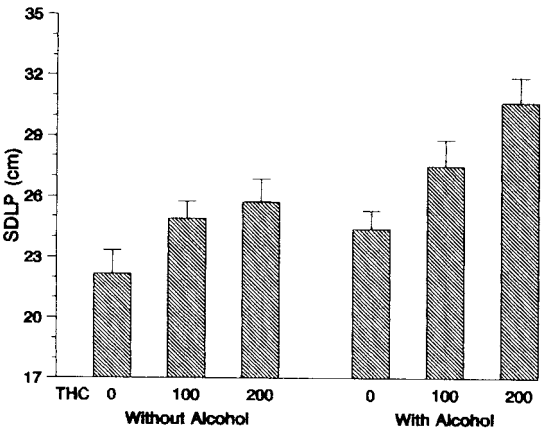

Figure 4. Mean (±SE) SDLP in the road-tracking test by THC dose and absence or presence of alcohol (averaged across repetitions)

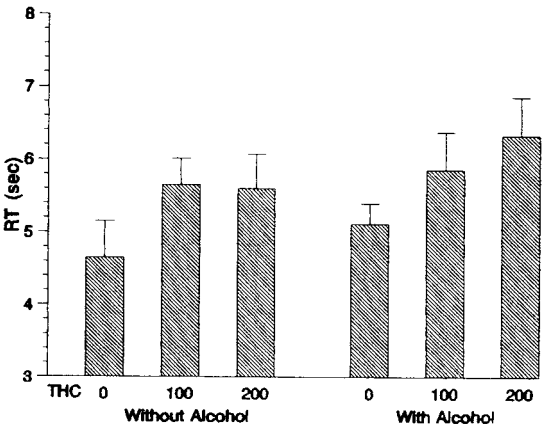

Figure 5. Mean (±SE) RT to decelerations in the car-following test by THC dose and absence or presence of alcohol (averaged across repetitions)

instructors spontaneously recorded several cases, usually in combined drug conditions, wherein a subject's aberrant behaviour would have been dangerous were he/she to operate the same way under natural driving conditions.

DISCUSSION

The results of Studies 1–3 corroborate those of previous driving simulator and closed-course tests by indicating that marijuana alone, with inhaled THC doses up to 300 μg/kg, has significant yet not dramatic impairing effects on driving performance (cf. Smiley, 1986). THC's effects are dose-related and persist unabated or even increase during 2·5 h after dosing. Standard deviation of lateral position in the road-tracking test was the most sensitive measure for revealing THC's adverse effects. This might be explained by the type of information processing required in each test. Road-tracking is primarily controlled by an automatic information processing system which operates outside of conscious control. The process is relatively impervious to environmental changes, but highly vulnerable to internal factors that retard the flow of information through the system. THC and many other drugs are among these factors. When they interfere with the process that restricts road-tracking error, there is little the afflicted individual can do by way of compensation to restore the situation. Car-following and, to a greater extent, city driving performance depend more on controlled information processing and are therefore more accessible for compensatory mechanisms that reduce the decrements or abolish them entirely.

The magnitudes of impairment observed after marijuana alone were not especially large in historical comparison to those of other drugs and never exceeded the equivalent effect of alcohol at a BAC of 0·08% (Louwerens *et al*, 1987; Robbe, 1994; Robbe and O'Hanlon, 1995; O'Hanlon *et al*., 1995). Yet THC's effects differ qualitatively from many other drugs, especially alcohol, as shown in the city driving test. Evidence from this and previous studies strongly suggests that alcohol encourages risky driving, whereas THC encourages greater caution, at least in experiments. Another way THC seems to differ qualitatively from many other drugs is that the former's users seem better able to compensate for its adverse effects while driving under the influence.

Although the effects of marijuana alone on driving performance were not dramatic in the present studies, they do imply a loss of driving ability that could be serious in other situations, for example, when combined with other drugs such as alcohol. The last study in the present series was designed to test this possibility and showed that the combination of THC with alcohol sufficient for attaining a BAC of about 0·04% has very severe effects on driving performance. Thus subjects with BACs below the per se definition of intoxication drove in a manner one would expect for drivers operating above the limit when they had smoked marijuana after drinking alcohol. That the subjects were able to safely demonstrate their impairment while under the influence of both drugs was, on occasion, only possible because of the driving instructor's intervention. Had these individuals attempted to drive alone under similar circumstances it is quite possible that one or more would have caused a serious traffic accident.

Inter-subject correlations between plasma concentrations of marijuana and driving performance after every dose were essentially nil, partly due to the peculiar kinetics of THC. It enters the brain relatively rapidly, although with a perceptible delay relative to plasma concentrations. Once there, it remains even at a time when plasma concentrations approach or reach zero. As a result, performance may still be impaired at the time that plasma concentrations of the drug are near the detection limit. This is exactly what happened in the first driving study. Therefore an important practical implications of the study is that it is not possible to conclude anything about a driver's impairment on

the basis of his/her plasma concentrations of THC and THC-COOH determined in a single sample.

In conclusion, while the effects of marijuana alone in doses up to 300 μg/kg might be categorized as 'moderate' they become 'severe' when low to moderate doses of alcohol are consumed prior to smoking marijuana.

ACKNOWLEDGEMENTS

The research program was sponsored by the US National Highway Traffic Safety Administration (NHTSA). Marijuana cigarettes were provided by the US National Institute on Drug Abuse (NIDA).

REFERENCES

De Gier, J. J. (1979). A subjective measurement of the influence of ethyl/alcohol in moderate doses on real driving performances. *Blutalkohol*, **16**, 363–370.

De Gier, J. J., 't Hart, B. J., Nelemans, F. A. and Bergman, H. (1981). Psychomotor performance and real driving performance of outpatients receiving diazepam. *Psychopharmacology*, **73**, 340–347.

Jones, M. H. (1978). *Driver Performance Measures for the Safe Performance Curriculum*. Traffic Safety Center, Institute of Safety and Systems Management, University of South California, Los Angeles, CA (DOT HS 803 461).

Klonoff, H. (1974). Marijuana and driving in real-life situations. *Science*, **186**, 317–323.

Louwerens, J. W., Gloerich, A. B. M., de Vries, G., Brookhuis, K. A. and O'Hanlon, J. F. (1987). The relationship between drivers' blood alcohol concentration (BAC) and actual driving performance during high speed travel. In *Alcohol, Drugs and Traffic Safety. Proceedings of the 10th International Conference on Alcohol, Drugs and Traffic Safety*, Noordzij, P. C. and Roszbach, R. (Eds), Excerpta Medica, Amsterdam, pp. 183–192.

Moskowitz, H. (1985). Marijuana and driving. *Accident Analysis and Prevention*, **17**, 323–346.

O'Hanlon, J. F., Vermeeren, A., Uiterwijk, M. M. C., van Veggel, L. M. A. and Swijgman, H. F. (1995). Anxiolytics' effects on the actual driving performance of patients and healthy volunteers in a standardized test: an integration of three studies. *Neuropsychobiology*, **31**, 81–88.

Robbe, H. W. J. (1994). Influence of marijuana on driving. Ph.D. thesis, Institute for Human Psychopharmacology, University of Limburg, Maastricht.

Robbe, H. W. J. and O'Hanlon, J. F. (1993). *Marijuana and Actual Driving Performance*. DOT HS 808 078, National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington D.C.

Robbe, H. W. J. and O'Hanlon, J. F. (1995). Acute and subchronic effects of paroxetine and amitriptyline on actual driving, psychomotor performance and subjective assessments in healthy volunteers. *European Neuropsychopharmacology*, **5**, 35–42.

Robbe, H. W. J. and O'Hanlon, J. F. (in press). *Marijuana, Alcohol and Actual Driving Performance*. National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington D.C.

Smiley, A. M. (1986). Marijuana: on-road and driving simulator studies. *Alcohol, Drugs and Driving: Abstracts and Reviews*, **2**, 121–134.

Terhune, K. W. (1992). *The Role of Alcohol, Marijuana and other Drugs in the Accidents of Injured Drivers*. Calspan Field Services Inc., Buffalo, New York. Tech. Rep. under Contract No. DOT-HW-5-01179.

