Marijuana, Alcohol and Actual Driving Performance

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The objective of the current study was to assess the separate and combined effects of marijuana and alcohol on actual driving performance. Eighteen subjects were treated with drugs and placebo according to a balanced, 6-way, crossover design. On separate evenings they were given weight calibrated Δ⁹-tetrahydrocannabinol (THC) doses of 0, 100 and 200 μg/kg with and without an alcohol dose sufficient for achieving blood alcohol concentrations (BAC) of 0.04 g/dl while performing a Road Tracking and Car Following Test in normal traffic. Main outcome measures were standard deviation of lateral position (SDLP), time driven out of lane (TOL), reaction time (RT) and standard deviation of headway (SDH). Both THC doses alone, and alcohol alone, significantly impaired the subjects performances in both driving tests. Performance deficits were minor after alcohol and moderate after both THC doses. Combining THC with alcohol dramatically impaired driving performance. Alcohol combined with THC 100 and 200 μg/kg produced a rise in SDLP the equivalent of that associated with BAC=0.09 and 0.14 g/dl, respectively. Mean TOL rose exponentially with SDLP. Relative to placebo mean RT lengthened by 1-6 s under the combined influence of alcohol and THC 200 μg/kg. Changes in SDH ranged between 0.9 and 3.8 m. Low doses of THC moderately impair driving performance when given alone but severely impair driving performance in combination with a low dose of alcohol.

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INTRODUCTION

There is no doubt that Δ⁹-tetrahydrocannabinol (THC) impairs its users' cognitive and psychomotor abilities to an extent largely determined by the inhaled or ingested dose. It is also certain that the dose preferred by cannabis smokers, i.e. around 300 μg/kg, is sufficient for impairing performance in potentially dangerous tasks such as driving (Robbe, 1994). It is less certain that those doses cause degrees of impairment that seriously compromise driving ability. Epidemiological surveys conducted in widely separated localities have generally revealed the presence of THC in between 4 and 12 per cent of drivers who sustained injuries or death in crashes (Terhune, 1982; Terhune et al., 1992; Cimbruna et al., 1980, 1982; Daldrup et al., 1987; Donelson et al., 1985; Garriot et al., 1986; Chester & Starmer, 1983; Budd et al., 1989; Soderstrom et al., 1988; McLean et al., 1987; Williams et al., 1985). Although the prevalence of THC users in the general driving population is generally assumed to be lower, these data cannot be accepted as evidence showing that THC was responsible for the crashes. The reason is that alcohol was also found in 50–90 per cent of the same drivers. The 1996 National Household Survey of Drug Abuse indicated that the concurrent use of alcohol is common among THC smokers in the US driving population (Townsend et al., 1998). Whereas 4 per cent of the respondents admitted to driving following the use of THC, about 80 per cent of the latter also reported the combined use of a low or moderate dose of alcohol. It was estimated that the vast majority of these drivers had estimated blood alcohol levels (BACs) less than 0.8 g/dl on these occasions. THC thus may offer the most hazardous potential when combined with alcohol. However, we know little about the exact nature and extent of any additional impairment to which THC increases driving impairment.

Numerous experimental studies in laboratories, driving simulators and closed-course tests have already been undertaken for that purpose (Attwood et al., 1981; Casswell, 1979; Peck et al., 1989; Smiley et al., 1987; Smiley, 1989; Stein et al.,

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1983; Chester, 1986; Liguori et al., 1998). To a large extent, the results from driving simulator studies and closed course tests corroborate the epidemiological finding by indicating little or no effects of THC alone in doses up to 250µg/kg; little or no effect of alcohol in BACs of 0.10 g/dl and nothing more than an additive effect of the two drugs in combination. In contrast to this, laboratory studies have repeatedly shown performance impairment occurring after inhaled doses as low as 40 µg/kg. This disparity in results obtained by laboratory tests and in driving simulations demonstrates that performance decrements under the artificial and non-life threatening conditions in the laboratory do not automatically predict similar decrements in driving simulations that are closer to the real world.

The present study emerged from a programme of research conducted at Maastricht University (Robbe, 1998). It differs from its predecessors by employing standardized tests for objectively measuring the drugs’ effects on driving performance in the natural environment, i.e., on real roads in normal traffic. It was expected that this study would provide better insight into the effect of THC on real-world driving, both when taken alone and when taken in combination with a low dose of alcohol.

METHODS

Subjects

Subjects were nine male and nine female volunteers, between 20 and 28 years of age. Volunteers were solicited by an advertisement in a local newspaper. Respondents were preliminarily screened to determine whether they fulfilled the inclusion criteria: current use of both alcohol and marijuana, with respective frequencies of once per week and once per month; and not on any medication. Each volunteer was required to have a valid driving licence, driving experience of at least 1000 km/year over the previous 3 years, and willingness to provide written informed consent. Their medical examination included a physical examination, a standard 12-lead ECG examination and routine laboratory determination of hematological and blood chemistry parameters.

Exclusion criteria were: history of drug (other than cannabis) or alcohol abuse or dependency; history of psychiatric, cardiovascular, respiratory, renal, hepatic, metabolic or neuromuscular disorders; presence of any drug in urine, besides cannabinoids; present use of medicinal drugs, except contraceptives; and for females, pregnancy. One unusual exclusion criterion was added by the local law enforcement authorities as a condition for their approval of the study: volunteers having any record of arrest for drug trafficking were to be excluded. For this purpose the Chief District Attorney for the City of Maastricht reviewed a list of volunteers’ names with their knowledge and consent. The study’s protocol was reviewed and approved in sequence by the District Attorney and the standing Medical Ethics Committee of Maastricht University. Subjects were treated according to the international convention governing drug studies with human volunteers; i.e., the Declaration of Helsinki (1964), and its subsequent amendments.

Design, doses and administration

Subjects were treated with drugs and placebo according to a balanced 6-way, observer- and subject-blind, crossover design. Subjects began treatments by drinking alcohol or alcohol placebo. They continued by smoking marijuana placebo or marijuana cigarettes delivering THC 100 or 200µg/kg. Six combinations of alcohol and THC were consumed by all subjects on separate evenings spaced one week apart: alcohol placebo+THC placebo (OO), alcohol placebo+THC 100µg/kg (OT1); alcohol placebo+THC 200µg/kg (OT2); alcohol+marijuana placebo (AO); alcohol+THC 100µg/kg (AT1); alcohol+THC 200µg/kg (AT2).

Alcohol dosing was designed to achieve a peak BAC of 0.06–0.07 g/dl before smoking and 0.04–0.05 during the driving tests. To achieve this, subjects ate two sandwiches while drinking the initial dose; i.e., 0.6 g/kg of ‘pure’ (99.8 per cent) ethanol mixed with orange juice to a volume of 300 ml and flavored with Grand Marnier essence for masking purposes. This was accomplished within 30 min. Subject’s BAC were monitored at 10 min intervals for 30–60 min after cessation of drinking using a Lion S-D4 Breath Alcohol Analyzer. Those failing to achieve the expected peak BAC were given a booster dose of 0.05–0.2 g/kg in the same proportion to the mixer, whereas others where given the mixer alone. A second booster dose was given midway through the driving tests in almost all cases for sustaining the desired BAC. Flavored orange juice was given at the same times and in approximately the same volumes in the placebo alcohol conditions. Smoking followed the cessation of the first alcohol dose by 60 min and continued...
for the following 10 min. The cigarettes were prepared beforehand for each individual from stock provided by the US National Institute on Drug Abuse. Originally, placebo cigarettes (i.e., containing marijuana leaf from which THC had been removed by ethanol extraction) and those containing the drug were all 85 mm in length and 25 mm in circumference, weighing about 800 mg. Cigarettes with THC concentrations of 2.2 per cent and 3.95 per cent were respectively used for providing 100 and 200 µg/kg doses. These were cut to provide lengths appropriate for the subjects’ weight. Subjects smoked them as completely as possible through a plastic holder in their customary fashion.

**Procedures**

Subjects were forbidden to smoke marijuana or hashish outside of the study, or to take any other illicit drug, from 7 days before their first session until the conclusion of the last. They were similarly forbidden to drink alcohol for 24 h before sessions. Subjects yielded breath and urine samples prior to each test session to confirm their compliance with prohibitions against prior use of alcohol and drugs. Driving tests began 30 min after smoking at 21:00 h. Initial drinking preceded smoking by 60 min. Subjects undertook the driving tests 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 on the highway for about 25 min, the first subject drove off and awaited the second. When he/she arrived, the pair exchanged roles, and drove in the reverse direction until returning to the origin. Both paused for 15 min after returning to the origin. Their BAC were monitored and a booster alcohol dose was given, if needed. Beginning around 22:15 h, the subjects drove through another circuit while repeating the same series of tests as before. Subjects rated their degrees of intoxication before and after the entire series of tests. They also rated the quality of their driving performance at the end of each test repetition. The instructors likewise rated the subject’s driving quality at the same times and in the same manner.

**Driving tests**

Subjects were accompanied by licensed driving instructors having access to redundant vehicle controls to insure safety at all times. In the Road Tracking Test (O’Hanlon et al., 1982), the subjects operated a specially instrumented vehicle over a 100 km primary highway circuit while maintaining a constant speed (95 km/h) and a steady lateral position between the delineated boundaries of the right (slower) traffic lane. An electro-optical device mounted at the rear back of the car continuously measured lateral distance separating the vehicle and the left lane line. This signal was digitized at a rate of 4 Hz and stored on an onboard computer disk file for later editing analysis. The off line editing routine involved removal of all data segments that revealed signal loss, disturbance or occurrence of passing maneuvers. The remaining data were then used to calculate means and variances for lateral position. Standard deviation of lateral position (SDLP) was taken as the primary outcome variable. SDLP is a measure of road tracking error, in practical terms, a composite index of allowed weaving, swerving and over-correcting. Failures to restrict the vehicle’s lateral motion within lane boundaries were recorded together as the percentage of time out of lane (TOL).

The Car Following Test (Brookhuis et al., 1987; Ramaekers & O’Hanlon, 1994) involved the use of two vehicles. The preceding vehicle was under an investigator’s control, and the following vehicle, the subject’s. The test began with the two vehicles traveling in tandem at speeds of 100 km/h (62 mph). Subjects attempted to drive 50 m (164 ft) behind the preceding vehicle and to maintain that headway as it executed a series of alternating acceleration and deceleration maneuvers lasting 33 s each. The investigator driving the preceding vehicle initiated each maneuver 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 (9.3 mph) 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 maneuver. About eight maneuvers in each direction were accomplished over both repetitions of the test. Headway was continuously recorded by means of a DME 2000 optical distance sensor. That device was placed in the grill of the following vehicle and emitted laser signals in the direction of a reflection board mounted on the leading vehicles towing bracket. Distance was deduced from the time lapse between the transmission and receipt of the signal at the receiving end of the distance sensor. Velocity of the leading vehicle was transmitted via telemetry to the

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following vehicle and stored on a computer disk along with the velocity of the following vehicle and headway. Speed signals collected during maneuvers entered a power spectral analysis for yielding phase-delay between the vehicle’s velocities at the maneuver cycle frequency (0.02) Hz. Phase delay converted to a measure of reaction time (RT) and the standard deviation of headway (SDH) were the major dependent variables.

Statistics
Multivariate analysis of variance (MANOVA) was applied to test the main effects of alcohol, THC, repetitions and their interactions on driving parameters. Univariate mean-pair contrasts between values recorded in the double-placebo condition and every other one were made using pooled error variance and sequential Bonferroni adjustment for multiple comparisons (Overall & Roades, 1985). Subjective parameters were analyzed by MANOVA for the effects of alcohol, THC, repetitions and their interactions. The between groups factor of rater was added to assess differences between subjects’ and instructors’ ratings of driving quality.

RESULTS
Blood Alcohol Concentration
Subjects’ BACs generally peaked in the range of 0.04–0.09 g/dl (mean ± SD, 0.067 ± 0.015 g/dl) within 1 h after drinking. Subjects began driving in every THC condition with mean BACs close to the legal limit of 0.05 g/dl. Mean BAC declined to about 0.035 g/dl over the course of the next hour. Booster doses were then administered to subjects with BACs below 0.05 g/dl, which arrested but generally did not reverse the decline. They achieved a mean BAC of about 0.04 g/dl 30 min later and finished driving with about 0.035 g/dl. Thus, most of the subjects performed the tests while their BACs fluctuated around 0.04 g/dl in a generally declining trend from about 0.05 to 0.035 g/dl.

Driving performance
Mean (± SE) SDLP values recorded in both repetitions of the Road Tracking Test within every treatment condition are shown in Figure 1. Subjects drove with the lowest mean SDLP after double placebo (i.e., in OO). Multivariate analysis revealed that the overall effects of alcohol ($F_{1,15}$=58.69; $p<0.001$) and THC ($F_{2,16}$=15.48; $p<0.001$) were highly significant. The main effect of Repetitions was also significant: subjects generally drove with higher SDLPs in the second test repetition than the first ($F_{1,15}$=10.49; $p<0.005$). However, the interactive effects of alcohol, THC and repetition were uniformly not significant. Every drug treatment significantly elevated SDLP, relative to double placebo, in separate mean-pair comparisons ($F_{1,15}$=5.19; $p<0.025$). Alcohol increased SDLP by 2.2 cm. THC 100 and 200 µg/kg increased SDLP by 2.7 and 3.5 cm, respectively, when taken without alcohol, and by 5.3 and 8.5 cm, respectively, when taken with alcohol.

Geometric mean (± SE) TOL is shown in Figure 2 for every treatment condition and repetition within conditions. Most subjects (i.e., 11) occasionally allowed the vehicle’s lateral motion to exceed lane boundaries while driving after placebo but the mean percentage of data recorded during these excursions was very low (i.e., 0.26 per cent). The overall effects of alcohol ($F_{1,15}$=17.08; $p<0.001$) and THC ($F_{2,16}$=4.67; $p<0.025$), though not repetitions, were significant. Mean-pair comparisons showed that the significant main effects were mainly attributable to the drug combinations. Whereas neither alcohol alone nor THC 100 µg/kg alone had appreciable effects, and THC 200 µg/kg alone had an effect that only approached significance ($p=0.077$), the two combinations very significantly elevated TOL.
Alcohol plus THC 100 μg/kg caused mean TOL to rise above 0-6 per cent, and alcohol plus THC 200 μg/kg, to about 1-1 per cent. The relationship between mean SDLP and TOL across both test repetitions in every condition is shown in Figure 3. The function describing that relationship was derived from least-squares regression analysis following an exponential model: \( TOL = 0.00359e^{0.18491SDLP} \). The empirical equation adequately describes the data \((R^2 = 0.89)\).

Mean RT in the Car Following Test did not differ significantly after drug and placebo, except after the combination of alcohol and THC 200 μg/kg. In that case, RT to decelerations increased by 1-6 s relative to double placebo \((p < 0.009)\). No treatment significantly affected mean headway. Mean values of headway varied irregularly between conditions from 41.9 m to 44.2 m. All of the mean differences from placebo in SDH were significant after \( p \) adjustment for multiple comparisons. Alcohol increased SDH by 0-9 m. THC 100 and 200 g/kg increased SDH with 2-9 and 3-8 m, respectively, when taken without alcohol, and by 2-5 and 3 m, respectively, when taken with alcohol.

**Intoxication Ratings**

Subjects began the various conditions making estimates of their degrees of intoxication that were reasonable considering the treatments given beforehand. Some at the beginning of the double placebo condition thought they felt something and reported low levels of intoxication (mean ± SD, 7-67 ± 2.37 per cent). However, nearly all reported stronger feelings after alcohol and both THC doses, given alone; i.e., 44-56 ± 5.48, 29-11 ± 4.20 and 36-50 ± 7.10 per cent, respectively. Combinations of alcohol with low and high THC doses produced still higher intoxication ratings; i.e., 52-89 ± 4.66 and 62-87 ± 4.90 per cent, respectively. In all conditions, mean intoxication ratings at the conclusion of testing were at levels about half of where they began. As might be expected, both the overall effects of alcohol and THC were highly significant \((F_{1,17} = 76.04, 19.76; p ≤ 0.001)\).

**Driving Quality Ratings**

Mean driving quality ratings by instructors and subjects are shown in Figure 4. Instructors rated the subjects’ performance as significantly worse than the subjects did themselves \((F_{1,17} = 7.26; p < 0.015)\). The mean differences were not large in magnitude and otherwise the two sets of ratings were quite similar. Ratings of the subjects’ performance in the Road Tracking Test clearly reflected the separate effects of alcohol \((F_{1,17} = 4.67; p = 0.045)\) and THC \((F_{2,16} = 13.62; p < 0.001)\). Somewhat surprisingly, those ratings did not show a separate significant effect of alcohol in the Car Following Test. THC’s effects \((F_{2,16} = 7.61; p = 0.005)\) were, however, also apparent in this context. Both subjects and instructors rated the subjects’ performance as generally worse in the first repetitions of both tests \((F_{1,17} = 23.41; p < 0.001)\).

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**Figure 2.** Geometric mean (± SE) of time out of lane (TOL, per cent) in first and second repetitions of the Road Tracking Test in every condition

**Figure 3.** Geometric mean TOL as a function of mean SDLP across conditions: OO (□), OT₁ (○), OT₂ (△), AO (■), AT₁ (●), AT₂ (▲)

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DISCUSSION
The subjects' performance in the Road Tracking Test clearly showed the adverse effects of alcohol and THC. Alcohol caused mean SDLP to rise by 2.2 cm over placebo levels. That change was almost exactly as predicted from a previously established alcohol calibration curve for drivers operating with 0.05 g/dl (Louwerens et al., 1987). That curve was based on the performance of social drinkers who performed the Road Tracking Test on five separate occasions while their BACs were controlled in equal steps between 0.00 and 0.15 g/dl. The drinkers' mean SDLP rose exponentially with BAC and an empirical equation was derived for calibrating the Road Tracking Test. The equation has subsequently been used for describing drugs' effects on SDLP in terms of respective BAC equivalencies. Separate doses of THC 100 μg/kg and THC 200 μg/kg caused mean SDLP to rise by 2.7 and 3.5 cm, respectively. These changes from placebo level were somewhat higher than those predicted from the calibration equation for driving with BAC=0.05 g/dl, the legal limit in most European countries. The effects of low doses of THC in this study were thus not blatantly dangerous, but they were certainly of sufficient magnitude to warrant concern. Drivers suffering the same degree of impairment as the present subjects did after THC alone would pose higher than normal risks to traffic safety.

The effects of combined alcohol and THC on the present subjects' road tracking performance were severe. Alcohol plus THC 100 and 200 μg/kg respectively elevated mean SDLP by 5.3 and 8.5 cm. The former change was comparable to that previously shown in social drinkers while driving with BAC=0.09 g/dl. The latter change was equivalent to driving with BAC=0.14 g/dl. These are important levels of impairment that are well above the legal limits of 0.08 and 0.1 g/dl that have been adopted by US states. Epidemiological studies in the US utilizing data from the Fatal Accident Reporting System in conjunction with driver exposure data from the second national road-side breath-testing survey, have found that between BACs 0.05–0.09 g/dl there is an 11-fold increased risk of fatal single vehicle crashes and between 0.10 and 0.14 g/dl the risk is 48 times greater (Zador, 1991).

The notion of high crash risks after alcohol and THC combined also follows from the exponential rise in TOL from conditions where alcohol and THC were separately administered to those where they were given in combination. It implies that the subjects' SDLPs could not have risen much further without a totally unacceptable increase in TOL. As it was, while mean SDLP increased from the lowest to the highest values in this study by 43 per cent, mean TOL rose by 474 per cent. Suspicion of a synergistic effect could not be confirmed by statistical tests that failed to show a significant interaction between alcohol and THC effects on TOL. Yet, there can be no doubt that their combination is potentially very dangerous for driving. Neither drug's doses in this study were particularly high and one may reasonably suppose that drivers in the real world occasionally operate after consuming more of one or both in combi-

Figure 4. Mean (± SE) ratings of driving performance in the Road Tracking (top) and Car Following Test (bottom), in each treatment condition, as scored by the driving instructors (▲) and the subjects (▼). Also shown are the frequencies of subjects failing the particular test-repetition according to themselves (S) and the instructors (I)

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nation. If they do, our results suggest that their increasingly large and frequent excursions from the relative safety of a traffic lane would occupy a considerable greater percentage of the distance traveled.

Results from the Car Following Test supported those from the Road Tracking Test. Mean SDH was significantly affected by every drug treatment. These changes in mean SDH indicate a diminished ability to perceive changes in the relative velocities of other vehicles and a diminished ability to adjust one’s own vehicle speed accordingly. Mean RT did not differ significantly after drug and placebo treatments, except in the worst case. Yet those differences were large in practical terms. The difference due to the combined effect of alcohol and THC 200 μg/kg was 1.6 s. Since the average speed in that condition was about 97 km/h, this delay meant that the vehicle traveled, on the average, an additional 42 m beyond the point where the subject began to decelerate after placebo treatment.

Subjects seemed well aware of their impairment in both tests. Their self-ratings of driving quality varied over conditions in general agreement with the objective measurement. The instructors rated their driving quality as even lower but the differences in these assessments were not very large. Some subjects, particularly after THC 200 μg/kg alone or in combination with alcohol, indicated that they had failed the tests. Why they continued to drive in these conditions is a good question. They probably would not have proceeded, nor undertaken the tests in the first place, were it not for their reliance on the instructors to prevent untoward consequences. Though reliance on the instructor was definitely not encouraged, it may be an inevitable artifact of this experimental approach.

It is clear from the present results that THC and alcohol combined produce serious impairment. Unfortunately, traffic police would not easily have recognized the level of impairment if the present subjects had been drugged driving under ordinary circumstances. None of the subjects would test positive on alcohol because their BAC values were below the legal limit in almost any country. Detection of marijuana use would also be highly unlikely. A review (Krüger et al., 1999) of legal regulations concerning drug driving revealed that in most European countries, as in the US, sanctions for drug driving depend on the evidence of reduced fitness as a consequence of drug consumption. The necessity of subsuming the drug-driving problem under the general impairment approach leads to problems in law enforcement: evidence of reduced fitness as a consequence of drug consumption is difficult to obtain because of a general lack of valid and practical drug recognition tests or programs (Gemmel et al., 1999). In recognition of this difficulty some countries attempt to introduce per se regulations with analytical limits for drug concentrations, analogous to BAC limits. However this poses the problem of how to set such a limit for individual drugs. Moreover, none of the present subjects would test positive for THC, if these limits were to reflect the same levels of impairment accepted at current BAC limits. Only an analytical zero limit, as introduced in Germany, would cause the present subject to fail the drug test. Consequently, THC smokers in the driving population can generally be expected to withdraw from legal regulations regarding drugs and driving when driving under the influence of alcohol and THC combined, particularly at low doses. When they do, our data suggest that they pose a serious threat to themselves and the general public.

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