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Effects of marijuana on equilibrium, psychomotor performance, and simulated driving

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Delta-9-tetrahydrocannabinol (THC) is frequently found in the blood of drivers involved in automobile accidents, and marijuana use has been associated with impaired field sobriety test performance. The present study used a within-subject design to compare the effects of marijuana (0, 1.77, or 3.95% THC) on equilibrium and simulated driving. Ten marijuana users (seven men, three women) smoked one marijuana cigarette at the beginning of each session. Then 2 min later, they began a 60-min test battery that included subjective effects scales, a computerized test of body sway, a rapid judgment task and brake latency measurement in a driving simulator, critical flicker fusion (CFF), and a choice reaction time task (CRT). Self-report ratings of 'high' and 'drug potency' increased comparably following both active doses. The high, but not the low, dose significantly increased body sway. The high dose also marginally increased brake latency by a mean of 55 ms ($P < 0.10$), which is comparable to an increase in stopping distance of nearly 5 feet at 60 mph Judgment, CFF, and CRT scores did not differ across dose conditions. The equilibrium and brake latency data with 3.95% THC are similar to prior results in our laboratory in participants with breath alcohol concentrations near 0.05%. Behav Pharmacol 1998; 9:599–609

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INTRODUCTION

Marijuana smoking has frequently been associated with automobile driving and automobile accidents. Approximately 50% of marijuana users aged 18–21 years reported either smoking marijuana while driving or driving under the influence of marijuana (Johnson and White, 1989). Across several studies, approximately one-third of injured or reckless automobile or motorcycle drivers had delta-9-tetrahydrocannabinol (THC) in their blood (Brookoff *et al.*, 1994; Kirby *et al.*, 1992; Soderstrom *et al.*, 1995). Marijuana impairment of driving performance has been reported in empirical studies that used simulators or actual automobiles (for review, see Moskowitz, 1985). In the earliest study of marijuana effects on simulated driving performance, participants were instructed to steer, signal for turns, and accelerate as they viewed a motion picture filmed from a moving vehicle (Crancer *et al.*, 1969). Only the speedometer reading was under direct control of participants; no driver maneuver altered the content or speed of the motion picture. Under the influence of marijuana, participants failed to drive within required speed limits. The dosing procedure and other design aspects of this study have been extensively criticized (Kalant, 1969). Two other studies of THC effects within driving simulators reported delayed reaction time to colored traffic light signals, but no impairment of other measures, such as lane tracking (Moskowitz *et al.*, 1976; Rafaelsen *et al.*, 1973). However, the use of motion pictures in these studies minimizes the interaction of driver and environment, thus limiting the interpretability of the results (Moskowitz, 1985).

In several experimental studies of driving on test tracks or in traffic, marijuana impaired lane tracking (Robbe, 1994) and other measures of car handling (Attwood *et al.*, 1981; Hansteen *et al.*, 1976; Klonoff, 1974). As in many simulator studies, the complexity of the driving situations in several of these road studies were limited compared to 'real-life' driving (Moskowitz, 1985), again limiting the interpretability of the data. Marijuana did not impair driving

performance in another on-road study, although several participants had difficulty walking to their vehicles and drove through the course much more slowly to compensate for their self-reported 'intoxication' (Sutton, 1983). The results of the latter study suggest that marijuana use is associated with avoidance of risk-taking driving maneuvers and increased body sway. A simulator study focused on risk-taking behavior reported that, relative to placebo, marijuana increased the number of times participants chose not to pass a car in their lane (Dott, 1972). Similar decreases in risk-taking driving behavior under the influence of marijuana have been reported in studies of both simulated driving (Ellingstad *et al.*, 1973; Smiley *et al.*, 1981) and driving in automobiles on roads (Klonoff, 1974). Marijuana impairment of equilibrium may be more severe following acute doses than with chronic use (Benowitz and Jones, 1975). Whether administered through marijuana smoking (Evans *et al.*, 1973; Greenberg *et al.*, 1994; Kiplinger *et al.*, 1971; Mathew *et al.*, 1992) or orally (Belgrave *et al.*, 1979; Chesher *et al.*, 1976), THC increases dizziness and body sway and impairs balance, even in standardized field sobriety tests (Heishman *et al.*, 1998).

Besides impairing performance on sobriety tests, marijuana also increases reaction time and may disrupt other psychomotor task performance (for review, see Chait and Pierri, 1992). In contrast, critical flicker fusion threshold – a measure of central nervous system excitability – has been enhanced by marijuana (1.5% THC; Schwin *et al.*, 1974). The authors described this marijuana effect as 'perceptual sharpening' comparable to that found with other stimulant compounds. The behavioral effects of marijuana may not always coincide with the drug's subjective 'high'. Heishman *et al.* (1988) have reported significant subjective effects of marijuana at doses (1.3 and 2.7% THC) that impaired performance on only one of several performance tasks.

The purpose of the present study was to compare the varied effects of marijuana within a driver by measuring mood, body sway, critical flicker fusion, choice reaction time, and simulated driving in adults using a within-subject design. The driving simulator was more interactive than those in prior studies; the images on the screen varied directly as a function of the driver's steering, braking, and acceleration. The simulator was used for tasks that separately measured response time to a road obstacle and rapid choice of the widest of three adjacent lanes. As we have reported the effects of different alcohol doses on most of these tasks (Liguori *et al.*, 1998), a secondary goal was to compare the effects of the present THC doses to those previously reported effects at breath alcohol concentrations between 0.05–0.10%.

METHODS

Subjects

Adult marijuana smokers between the ages of 21–45 years were recruited via newspaper advertisements and initially interviewed by telephone. Potential participants were excluded if they did not have a current driver's license or if they reported: daily or less than weekly use of marijuana; the use of more than 14 standard alcohol drinks per week; smoking more than one pack of cigarettes per day; current use of prescription or illicit psychoactive drugs other than marijuana; a history of drug dependence (not including nicotine dependence) or drug counseling; a history of a prior or current psychiatric disorder; being pregnant, planning to become pregnant, or breast feeding; or having less than 5 years' driving experience.

Those persons who were not excluded underwent an extended drug history interview with the principal investigator at the laboratory. If a potential participant had used marijuana on less than four, or more than 28, of the prior 30 days, that participant was excluded from the study. Otherwise, the participant gave informed consent. A physical examination that screened for neurologic and cardiopulmonary abnormalities and included a medical history was administered by a physician before participation began.

Twenty-four respondents met the inclusion guidelines and gave informed consent. Fourteen of these 24 participants withdrew or were excused from the study, often before the study began ($n = 11$). The most common reason for this attrition was one or more absences at the scheduled physical examination ($n = 7$).

The remaining 10 participants (three females and seven males) completed the study. Their mean [$\pm$ standard deviation (SD)] age was 29 ± 6 years. Eight participants (two females and six males) were primarily Caucasian, and the other two were primarily African-American. All participants reported prior marijuana use on at least 40 occasions (lifetime) and on a mean of 12 ± 7 of the prior 30 days. They reported drinking an average of 4 ± 2 alcoholic drinks per week. Those who smoked tobacco cigarettes (two females and three males) reported smoking an average of 12 ± 5 cigarettes per day. Two participants reported no prior use of illicit drugs other than marijuana. Among the other eight

participants, six reported prior use of cocaine, five had used hallucinogens, four had used amphetamines, two had used alprazolam, two had used benzodiazepines, and one reported use of prescription opiates and inhalants. No participant reported using illicit or prescribed psychoactive drugs in the prior four months.

Participants were told that the study would measure 'marijuana versus placebo effects on cognition, balance and simulated driving'. Each participant was compensated $200 for completing the study.

General procedure

The experimental protocol was approved by the Clinical Research Practices Committee of Wake Forest University School of Medicine. All participants attended four laboratory sessions. During the first (practice) session, participants received no drug but completed all other procedures to acquaint themselves with the equipment, forms, and tasks. Participants were driven to the laboratory by taxi for the next three (drug) sessions. Drug sessions were separated by at least 6 days. Participants were instructed to abstain from marijuana for 48 h before each session, from caffeine and alcohol for 36 h before each session, from cigarettes for 1 h before each session, and from other psychoactive drugs for the duration of the study. Abstinence from caffeine use was verified by saliva sampling and analysis. Saliva samples were analyzed for caffeine concentrations on the session day with the Behring Diagnostics Caffeine Assay Kit (Behring Diagnostics Inc., Cupertino, CA, USA), which is a homogenous enzyme immunoassay. All samples contained less than 1.2 μg/ml caffeine, and all but two contained less than 0.5 μg/ml caffeine, which is consistent with levels found in other studies after overnight abstinence (Evans *et al.*, 1994; Liguori and Hughes, 1997). Abstention from recent alcohol use was verified by measurement of breath alcohol concentration (BrAC) with a hand-held meter (Intoxilizer S-D2, CMI Inc., Owensboro, KY, USA). Abstention from psychoactive drugs was verified by urinalysis (Triage panel, BIOSITE, San Diego, CA, USA).

After pre-session urine and saliva sampling, each participant's heart rate, blood pressure, BrAC, and carbon monoxide level was measured, and participants completed and passed a field sobriety test. Participants then completed several baseline paper-and-pencil subjective effects questionnaires described below.

Next, participants received one marijuana cigarette and smoked it within 5 min as described below. Two minutes after finishing the cigarette, participants completed a 1-h test battery. After the test battery, participants were allowed to eat, read, and rest in the laboratory. Upon passing a field sobriety test 3.5 h after smoking that session's cigarette, participants were driven home by taxi service. Four participants failed the initial field sobriety test at the conclusion of a drug session. Each of these participants passed a second test after an average of 35 min (range 15–58 min), then were driven home.

Marijuana administration

The marijuana cigarettes were prepared and supplied by the National Institute on Drug Abuse. The cigarettes were approximately 85 mm in length and 25 mm in circumference and contained 0.00, 1.77, or 3.95% THC. Cigarettes were stored in airtight containers in a freezer and humidified for 24 h before test sessions. Each cigarette was placed in a hollow plastic cigarette holder and smoked according to a method previously described (Higgins and Stitzer, 1986). Specifically, participants repeated the following cycle through 10 inhalations and exhalations: inhale with *ad libitum* duration and puff volume, hold inhalation in lungs for 7 s, exhale, inhale 30 s after prior inhalation began. This procedure resulted in pyrolysis of approximately 80% of the cigarette regardless of dose.

Test battery

The test battery consisted of an 'equilibrium-CFF-CRT' component and a 'driving simulator' component. To avoid the influence of acute tolerance on the results, the order of these components and the order of the tasks within these components were randomized for each session and each participant. Between the components, several subjective effects scales were administered and physiological measures were collected (see 'Subjective effects component' below).

Equilibrium-CFF-CRT component

Equilibrium

A computerized sensory organization test (EquiTest, Neurocom International Inc., Clackamas, OR, USA) was used to measure dynamic posturography. During this test, participants stood on a platform and faced a surrounding wall illustrated with a colorful abstract landscape. Across six conditions, vision (eyes open or closed), the platform (stable or 'sway-referenced'), and the visual surround (stable or 'sway-referenced') were manipulated (see Table 1). When the platform or wall was sway-referenced, its movements matched

TABLE 1. Characteristics of each condition in the sensory organization test

Condition	Eyes	Support	Vision	Rationale
1	Open	Fixed	Normal	Control condition[a,b,c]
2	Closed	Fixed	Absent	Isolates somatosensory cues[a,d]
3	Open	Fixed	Sway-referenced	Inaccurate visual information, accurate somatosensory cues[d]
4	Open	Sway-referenced	Normal	Isolates visual cues[b]
5	Closed	Sway-referenced	Absent	Isolates vestibular cues[c,d]
6	Open	Sway-referenced	Sway-referenced	Inaccurate visual information, inaccurate somatosensory cues[d]

Cue scores (computed as condition score ratios × 100):
[a]Somatosensory = 2/1; [b]visual = 4/1; [c]vestibular = 5/1; [d]visual preference = (3 + 6)/(2 + 5).

the participant's anteroposterior body movements that maintained upright posture. The goal of sway-referencing was to determine changes in balance when visual information (surrounding wall), somatosensory information (platform), or both were inaccurate.

Each condition included three 20-s trials. The limits of stability of the EquiTest were an 8.5° anterior sway or a 4° posterior sway, for a total of 12.5° sway from initial alignment of upright posture. For each trial, an 'equilibrium score' was calculated based on ((12.5 − (maximum anterior sway + maximum posterior sway))/12.5) × 100. Thus, a participant who does not sway at all would receive a score of 100, while a participant whose body sway approached the limits of stability in both directions would receive a score near 0. Any participant who fell during a trial received a score of 0 for that trial.

The three trial scores within a condition were averaged to produce a condition score. The mean of condition 1, the mean of condition 2, and the individual trial scores from conditions 3–6 were averaged to derive a composite equilibrium score. Reliance on somatosensory, vestibular, and visual cues was quantified with ratios of the condition scores (see Table 1). Lower somatosensory, vestibular, or visual cue scores indicated decreased ability to use those particular cues; higher visual preference scores indicated increased reliance on visual cues, even when those cues were inaccurate.

Critical flicker fusion (CFF)

Seated participants observed four red light-emitting diodes from a distance of approximately 1 m. The participants identified the frequency at which flickering light became fused light (or vice versa) by pressing a hand-held switch. Three flicker-to-fusion ('rising') trials and three fusion-to-flicker ('falling') trials were alternated during each session. The means of these three-trial sets and the overall six-trial mean were used in data analyses.

Choice reaction time (CRT)

Seated participants reacted to randomly illuminated lights on a panel by moving the index finger of the right hand from a central 'home' pad to a pad next to one of six red illuminated 'target' lights then back to the home pad. The home pad was adjacent to a green light that extinguished when the pad was touched. The target lights were arranged in a semicircle with each light 15 cm from the home pad. Mean data collected from 20 trials included latency to remove the index finger from the home pad when a red light is illuminated (recognition reaction time), latency to touch the pad adjacent to the target light (motor reaction time), and the sum of the recognition and motor reaction times (total reaction time).

Subjective effects component

The Profile of Mood States (McNair *et al.*, 1971) and several visual analog scales were administered immediately before and approximately 30 min after participants began smoking their cigarette. Immediately following the completion of these scales, heart rate, blood pressure, and carbon monoxide concentration (CO) were measured.

Profile of mood states (POMS)

Respondents complete the POMS by identifying how strongly (not at all, a little, moderately, quite a bit, or extremely) they are experiencing each of 65 feelings. Each score was incorporated in one of seven subscales: anger-hostility, confused-bewildered, depression-dejection, fatigue, tension-anxiety, vigor, and friendliness. Friendliness scale data were not analyzed because of the scale's limited validity (McNair *et al.*, 1971). Difference scores (post-drug

minus pre-drug) from the other six scales were analyzed.

Visual analog scales (VAS)

Each VAS consisted of a question (e.g. 'Do you feel high?') below which a 100-mm line indicated the range of responses from 'not at all' to 'extremely'. Respondents indicated their answer by drawing an intersecting line through the 100-mm line. The scale items asked if participants felt high, stoned, drunk, impaired, energetic, clear-headed, anxious, sluggish, confused, and relaxed (Azorlosa *et al.*, 1992). Difference scores (post-drug minus pre-drug) from these scales were analyzed. Four additional post-drug visual analog scales asked participants to rate the taste, harshness, draw, and potency of that day's marijuana cigarette.

Physiological measures

Heart rate and blood pressure were measured with an electronic wrist monitor (Omron Healthcare Inc., Vernon Hills, IL, USA), and CO was measured with a hand-held meter (Vitalograph, Vitalograph Inc., Lenexa, KS, USA). These measures were collected after completion of the POMS and VAS.

Driving simulator component

The AGC mobile operations simulator (AMOS) model SV5000LE (Time Warner Interactive, Milpitas, CA, USA) is a chamber with five video monitors (63 cm diag.) arranged in a semicircle around a driver's seat. Each monitor is approximately 65 cm from the driver's eyes. Beneath the third (center) monitor is a steering wheel mechanism with ignition and gearshift. During driving simulation, the room's overhead light was turned off. The simulator component consisted of 'barrier' and 'judgment' tasks.

Barrier

During the driving simulation, participants saw an open stretch of highway on the center monitor and a mountainous horizon across all five monitors. Participants were instructed to start the car and drive on the highway, accelerating to 55 miles per hour (mph) as quickly as possible and keeping their speed between 55–60 mph. To insure compliance with these instructions, a tone was emitted through the dashboard if the vehicle's speed fell below 55 mph, and another, higher-pitched, tone was emitted if the vehicle's speed rose above 60 mph. After the vehicle traveled a randomly determined distance (mean ± SD = 1.3 ± 0.7 mi; range, 0.4–2.2 mi), a yellow barrier fence suddenly appeared in the direct path of the vehicle on the center monitor. Participants were instructed to brake as quickly as possible to stop the vehicle and avoid hitting the fence. Latencies to release the accelerator (accelerator-release latency) and to press the brake pedal (brake latency) following the appearance of the barrier were measured across five trials. To ensure consistency of topography across trials, the latency data from a given trial were discarded if the participant either did not have a foot on the accelerator or used more than one foot to stop the vehicle. Less than 6% of the data (range between zero and three of each set of five) was discarded.

Judgment

Drivers were instructed to maintain a speed of 30 m.p.h. through this task. Participants drove through a lane defined by cones, then saw three parallel lanes of varying widths, also defined by cones. The driver had to choose the lane that seemed widest, drive through it without decelerating, then stop the vehicle. If the correct lane was chosen, the word 'correct' would briefly appear on the center monitor. Measures included mean speed, number of cones knocked over, and percentage of correct lane choice. Each participant completed five trials within each drug session.

Data analysis

Mean scores associated with the EquiTest, driving simulator, CFF and CRT tasks, change scores for the POMS, VAS, systolic and diastolic blood pressure, heart rate, and CO, and individual scores on the VAS cigarette rating scales were entered into separate one-way repeated measures analyses of variance with dose (placebo, 1.77, and 3.95% THC) as the factor. Unless general linear models tests were used (see below), reported *P*-values were adjusted based on Huynh–Feldt probabilities. Tukey *post-hoc* multiple comparisons were used when significant effects ($P < 0.05$) were found.

Outliers and missing data

In analyses of the CRT and 'barrier' data, outliers were determined based on the mean and SD for that session's 20 trials. An outlier was defined as a trial with a recognition, motor, or total reaction time that differed from the mean of that session's 20 trials by four standard deviations or more. Such trials were excluded from analyses, and the mean recognition, motor, and total reaction times for that session were

redetermined. Using this method, less than 2% of CRT data (11 of 600 trials) were excluded, and no more than one trial was excluded per session. No outliers were found among the 'barrier' data with these criteria.

A mechanical error invalidated a single session's 'barrier' and 'judgment' data for two participants. The entire session was replicated for one participant, and data from the replicated session were used in analyses. The other participant was unavailable for rescheduling. Thus, analyses of 'barrier' and 'judgment' data used the SAS GLM procedure (SAS Institute, Cary, NC, USA) and adjusted the degrees of freedom and the mean square error term to compensate for the single missing data point.

RESULTS

Physiological measures

Across subjects, mean (± SD) pre-drug systolic blood pressure was 119 ± 13 mmHg, diastolic blood pressure was 68 ± 6 mmHg, heart rate was 73 ± 7 beats per minute (bpm), and CO was 8 ± 9 parts per million (ppm). Within 2 min of smoking, both marijuana doses increased heart rate, $F(2,18) = 23.5$, $P < 0.001$, although the mean [± standard error of mean (SEM)] increases with the 1.77 and 3.95% doses (24 ± 5 and 36 ± 6 bpm, respectively) did not significantly differ. CO boost (± SEM) was marginally greater with placebo (mean increase 10.4 + 2.0 ppm) than with the 1.77 and 3.95% doses (8.9 ± 1.9 and 8.1 ± 1.5 ppm, respectively), $F(2,18) = 2.8$, $P < 0.10$. Systolic and diastolic blood pressure did not differ across the three dose conditions.

Subjective effects

Profile of mood states (POMS)

On the tension subscale, the 3.95%, but not the 1.77%, THC dose significantly increased scores over placebo scores, $F(2, 18) = 4.4$, $P < 0.05$ (see Figure 1). Neither dose significantly changed scores on the anger, depression, confusion, fatigue, or vigor subscales.

Visual analog scales (VAS)

Both doses comparably increased ratings of 'high', $F(2,18) = 25.0$ and 'stoned', $F(2,18) = 28.5$, over ratings with placebo ($P < 0.001$; see Figure 1). The 3.95%, but not the 1.77%, THC dose significantly

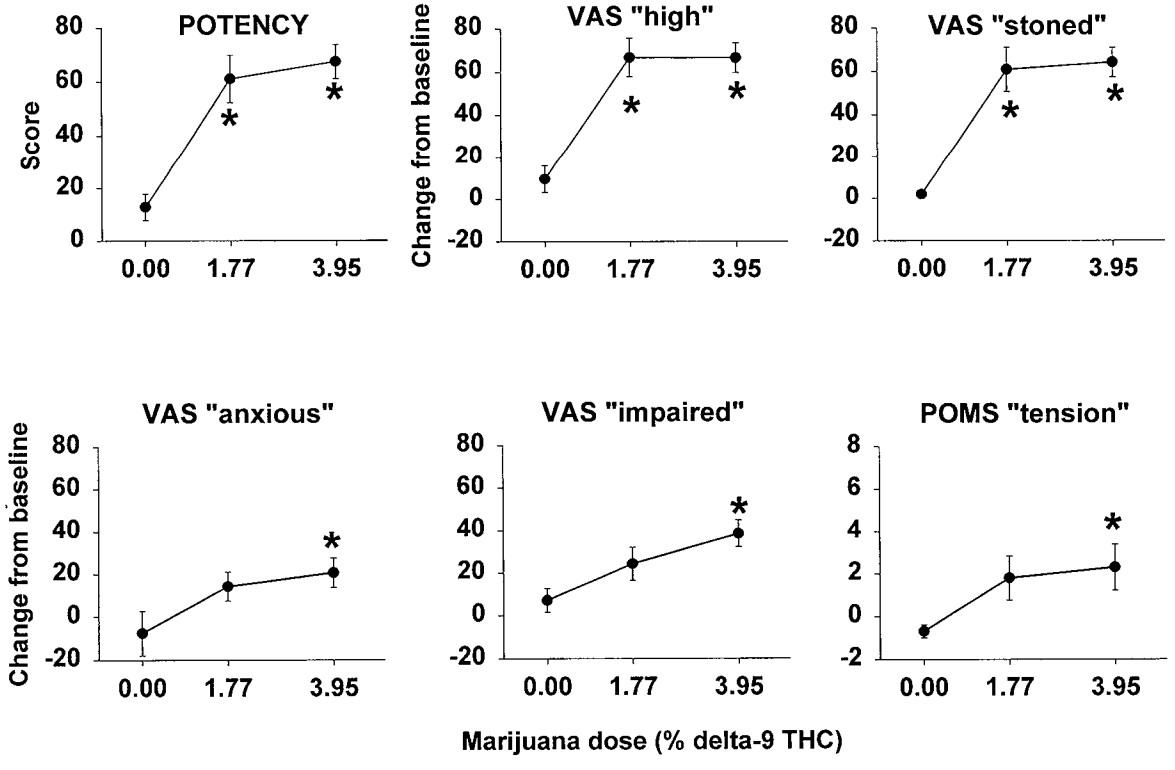

FIGURE 1. Mean changes (from pre-drug) in ratings of cigarette potency, visual analog scale ratings of 'high', 'stoned', 'anxious', and 'impaired', and POMS tension scale scores as a function of delta-9-tetrahydrocanabinol (THC) dose (n = 10). Error bars, 1 SEM. *Significantly different from placebo, $P < 0.05$.

increased ratings of 'anxious', $F(2,18) = 4.0$ and 'impaired', $F(2,18) = 9.7$ ($P < 0.01$; see Figure 1). Neither dose significantly changed scores on the 'clear-headed', 'confused', 'drunk', 'energetic', 'relaxed', or 'sluggish' scales.

Compared to placebo, both doses significantly and similarly increased ratings of 'potency', $F(2, 18) = 25.8$, $P < 0.001$ (see Figure 1). The two doses and placebo did not significantly differ with respect to ratings of draw, harshness, or taste.

Equilibrium-CFF-CRT effects

Dynamic posturography

Composite equilibrium scores were lower with 3.95% THC than with either 1.77% THC or placebo, $F(2, 18) = 6.9$, $P < 0.02$ (see Figure 2). The 3.95%, but not 1.77%, THC dose significantly decreased vestibular cue scores, $F(2,18) = 4.0$, $P < 0.05$. Somatosensory, visual, and visual preference cue scores did not differ across dose conditions (see Figure 2).

Critical flicker fusion

Mean rising, falling, and overall critical flicker fusion thresholds did not differ as a function of dose.

Choice reaction time

Mean recognition, motor, and total reaction times did not differ across dose conditions (see Table 2).

Simulated driving

Barrier

As shown in Table 2, the difference in mean brake latency across the two THC doses and placebo was marginal, $F(2,17) = 2.8$, $P = 0.087$. This result was due to the effects of the 3.95% THC dose, which increased brake latency by 54 ms, rather than the 1.77% THC dose, which increased brake latency by 38 ms (see Table 2). Mean recognition and motor reaction times did not differ across dose conditions.

TABLE 2. Comparison of recognition, motor, and total reaction times (ms) across choice reaction (CRT) and barrier tasks[a]

Dose	CRT			Barrier		
(Δ-9THC)	Recognition	Motor	Total	Recognition (accelerator-release)	Motor	Total (brake latency)
0.00%	348 ± 12	281 ± 13	630 ± 19	350 ± 17	240 ± 14	590 ± 28
1.77%	354 ± 10	285 ± 13	639 ± 20	370 ± 12	258 ± 16	628 ± 19
3.95%	363 ± 15	277 ± 18	641 ± 29	366 ± 16	278 ± 20	644 ± 18[b]

[a]Values are means ± SEM; [b]different from placebo, $P < 0.10$.

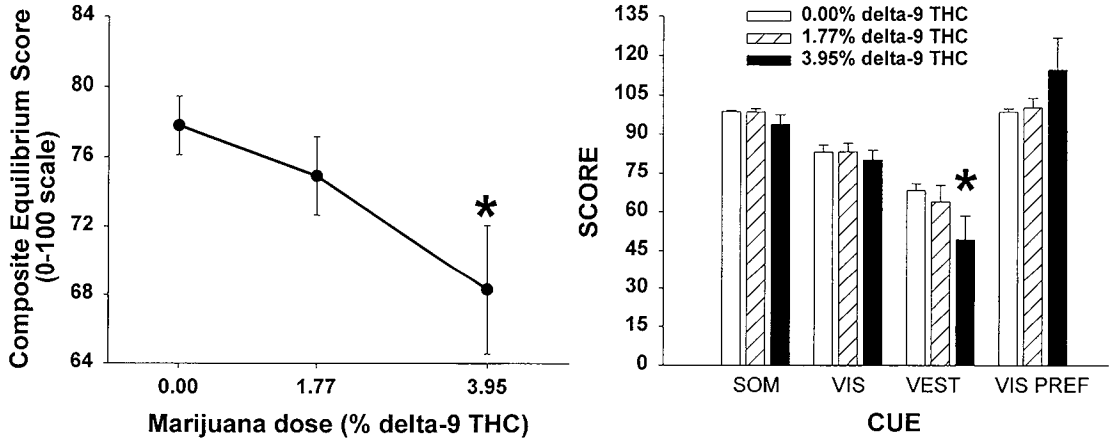

FIGURE 2. Left: mean composite equilibrium score as a function of delta-9-hydrocannibol (THC) dose (n = 10). Right: mean somatosensory (SOM), visual (VIS), vestibular (VEST), and visual preference (PREF) cue scores (n = 10). Error bars, 1 SEM. *Significantly different from placebo, $P < 0.05$.

Judgment

With the placebo cigarette, participants' mean (± SD) speed through the course was 34 ± 2 mph. Also with placebo, participants averaged 1.3 ± 0.7 cones knocked over per trial and 3.8 ± 1.0 correct lane choices across the five trials. These measures did not differ across dose conditions.

DISCUSSION

In the present study, a THC dose that caused increases in heart rate, self-reported anxiety and self-reported tension also increased body sway and produced a trend toward delays in drivers' response to the appearance of a road obstacle in a simulated driving task. A lower dose, associated with a comparable self-reported 'high' and a more modest increase in heart rate, produced no significant behavioral effects. These results extend previous reports of marijuana impairment of general field sobriety tests (Heishman *et al.*, 1998) by illustrating that marijuana users with impaired balance may react more slowly in potentially dangerous situations while driving an automobile.

When the effects of marijuana on visual, somatosensory, and vestibular cues were analyzed separately, only vestibular cues were significantly impaired. Such vestibular impairments can often lead to dizziness and nausea (Kelly, 1985). This result illustrates that when smoking marijuana of sufficiently high potency, marijuana users must rely more heavily on vision and somatosensory cues for maintenance of stable posture. Whereas increased dizziness while standing (Mathew *et al.*, 1992) and increased body sway during standing steadiness and dynamic posturography testing (Evans *et al.*, 1973; Greenberg *et al.*, 1994; Kiplinger *et al.*, 1971) have previously been shown among marijuana users, we know of no previously published research measuring marijuana's effects on sensory organizational testing using the EquiTest system as in the present study. The effects of 3.95% THC on balance appear comparable to those of moderate alcohol in prior studies that have used this equipment. Two studies (Ledin and Odkvist, 1991; Tianwu *et al.*, 1995) reported increases in participants' body sway at a BrAC of approximately 0.05% when participants' eyes were closed and the platform was sway-referenced. Compared to data from a prior study of moderate alcohol drinkers in our laboratory (Liguori *et al.*, 1998), composite equilibrium scores with the 3.95% THC dose in the present study did not significantly differ from scores at a BrAC of 0.05%, but were significantly better than scores at a BrAC of 0.10%.

Brake latency while driving under the influence of the 3.95% THC dose also appears similar to brake latency while driving with a BrAC of 0.05%. In a prior study of moderate alcohol drinkers (Liguori *et al.*, 1998), mean brake latency with placebo (593 ms) was similar to mean brake latency with placebo cigarette in the present study (590 ms). The mean 54-ms increase in brake latency with the 3.95% THC cigarette in the present study was comparable to the previously reported mean increases of 40 ms in participants whose BrAC was 0.05% at the time of testing.

Comparison of marijuana's effects on the barrier versus choice reaction time tasks suggests that the degree of marijuana impairment may be related to task complexity. The 3.95% THC cigarette tended to increase brake latency but did not similarly impair performance on the relatively less complex choice reaction time task. In prior studies, effects of marijuana on reaction time have been inconsistent, with some studies reporting significant slowing (Wilson *et al.*, 1994) and others reporting no effects (Heishman *et al.*, 1997). Overall, impairments from marijuana have been more frequently reported on complex rather than simple reaction time tasks (Chait and Pierri, 1992; Moskowitz, 1985). One explanation for this trend is that the essential factor impaired within a given reaction time task is not speed, but information processing (Moskowitz, 1985). Extending this reasoning to the present study, the identification of the barrier amidst the many stimuli available to a driver (e.g. road, sky, landscape) requires more information processing – and is likely to be more subject to impairment – than the identification of an illuminated light on a black panel in the choice reaction time task.

The lack of significant dose effects on the CFF task suggest that perceptual sensitivity while driving may be unaffected by marijuana. Although THC has previously been shown to enhance CFF thresholds (Schwin *et al.*, 1974), the present finding is consistent with more recent research. In a tachistoscopic study of visual information processing, marijuana did not affect the threshold duration necessary for correct identification of a stimulus letter. When that letter was 'masked' with the subsequent presentation of another stimulus, marijuana decreased detection accuracy (Braff *et al.*, 1981). Similarly, Leweke *et al.* (1998) have reported that THC impaired recognition accuracy without affecting reaction time. In both of these studies, perception was apparently unaffected by THC while information processing was slowed.

If marijuana is most likely to impair performance on tasks involving information processing, our failure to detect an effect of marijuana on the judgment task is surprising. Because it requires additional skills, the judgment task appears more complex than the barrier task. Besides maintenance of a particular speed as in the barrier task, the judgment task also requires decision making, tighter steering, and avoidance of many obstacles (cones) rather than a single fence. Several possible explanations exist for this finding. First, vehicle speed may interact with behavioral drug effects, as the car travelled nearly 70% faster in the barrier task than in the judgment task. Increasing the speed at which participants must choose and drive through the widest lane might result in increased errors.

Alternatively, the sudden random appearance of the key stimulus may be necessary for demonstration of marijuana impairment. In the barrier task, the fence could appear anywhere between 0.4 and 2.2 miles from the beginning of the trial. In the judgment task, the three lanes always appeared at the same point within the course. If the time-point of the appearance of the three lanes were randomized in the same fashion as the appearance of the barrier fence, similar delays in response may have occurred.

A third possibility is that drivers under the influence of marijuana are more cautious than usual, and as a result are more aware of potential dangers in the road. Across several studies of simulated driving, participants in scenarios for passing other vehicles were less likely to do so or did so more cautiously following marijuana use than following placebo (Dott, 1972; Ellingstad *et al.*, 1973; Smiley *et al.*, 1981). These results suggest that marijuana may have increased careful driving in our judgment task and that rapid judgment tasks even more complex than that used in the present study may not be sensitive to THC impairment.

Some subjective effects of marijuana did not coincide with behavioral impairment. Participants reported feeling 'high' and 'stoned' following 1.77% THC, but no concurrent behavioral effects were found. Although several authors have reported correlations between mood and performance effects of marijuana (Cone *et al.*, 1986; Wilson *et al.*, 1994), others have reported subjective effects of marijuana without task performance effects (Heishman *et al.*, 1988). Nonetheless, participants in the present study were likely to identify themselves accurately as impaired. Although their cigarette evaluations produced similar potency ratings of the two active doses, participants only reported higher 'impairment' when they received the dose that concurrently impaired equilibrium and tended to increase brake latency. This finding is consistent with prior reports of congruent subjective and behavioral impairment following marijuana (Heishman *et al.*, 1988, 1997).

The increases in heart rate with both active doses illustrate absorption of THC by the participants (Chait and Pierri, 1992; Higgins and Stitzer, 1986). In the present study, as in prior studies with paced smoking procedures, two active doses produced comparable heart rate increases (Higgins and Stitzer, 1986) and similar subjective ratings of cigarette potency and 'high' (Heishman *et al.*, 1988). As puff volume was controlled by participants in the present study, the participants may have inhaled a lower volume of smoke per puff with the high-potency cigarette than with the low-potency cigarette. Because variations in puff volume may produce dose-related changes in subjective effects and plasma levels of marijuana (Azorlosa *et al.*, 1995), controlling puff volume across doses may have produced a more linear increase in heart rate and subjective high with increasing THC dose. Another aspect of smoking that may influence subjective effects is breath-hold duration. This was held constant at 7 s in the present study, but increased 'high' ratings with a 15-s breath-hold compared to a 7-s breath-hold have been reported elsewhere (Block *et al.*, 1998). The effects of breath-hold duration may be limited, however, as a ceiling effect appears to occur with breath-holds longer than 10 s (Azorlosa *et al.*, 1995).

In summary, the present results suggest that marijuana may impair several key aspects of driving behavior, particularly reaction time and maintenance of stable upright posture. Based on comparisons to prior studies in our laboratory, the effects of 10 puffs on a 3.95% THC cigarette on these tasks appear similar to those of a BrAC of 0.05%. This relation is comparable to that reported in a direct, within-subject comparison in which subjective and psychomotor effects of 16 puffs on a 3.55% THC cigarette versus a BrAC of 0.09% were similar (Heishman *et al.*, 1997). Whether a higher THC dose is comparable to a higher alcohol breath concentration is of particular relevance because currently available marijuana in the USA likely has a higher potency than that used in the present study. One analysis of over 800 seized marijuana cigarettes in late 1997, revealed a mean concentration of 4.56% THC (ElSohly and Ross, 1998). A direct empirical comparison of marijuana and alcohol effects on equilibrium and simulated driving is needed to confirm and extend the relation between THC and alcohol effects.

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