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The effects of cannabis and alcohol on simulated driving: Influences of dose and experience

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ABSTRACT

Background: Cannabis and alcohol are the most popular drugs amongst recreational users, and most prevalent in injured and deceased drivers. Clarification of the interactive effects of these drugs upon driving behaviour is critical for reducing drug-related road deaths.
Objectives: The current study had two objectives, to examine the effects of cannabis and alcohol on driving performance, and identify if any differences between the effects of cannabis and alcohol on driving performance exist between regular cannabis users and non-regular cannabis users.
Methods: The project involved 80 participants (49 male, 31 female) who were abstinent recreational users of alcohol and marijuana. They participated in six experimental sessions that involved the consumption of cannabis cigarettes containing no THC, 1.8% THC or 3% THC together with the consumption of alcohol to obtain either 0% BAC, 0.03% BAC or 0.05% BAC. The six sessions were double-blind, counter-balanced, placebo-controlled and medically supervised. Forty participants were allocated to the cannabis with low alcohol (0.03% BAC) group, and 40 participants were allocated to the cannabis with high alcohol (0.05% BAC) group. Driving simulator performance was assessed at 20 min post-drug administration and blood samples were taken before and after driving.
Results: Driving simulator performance was more impaired in the THC and alcohol combined conditions. Consistent with past research, the level of THC detected in blood is higher when THC is consumed with alcohol, than when cannabis is consumed alone, and regular cannabis users returned higher levels of THC in plasma than non-regular users. Generally, regular cannabis users displayed more driving errors than non-regular cannabis users.

1. Introduction

Driving under the influence of drugs alone or in combination with alcohol is widely reported to impair driving (Penning et al., 2010). Growing research interest in the specific effects of driving under the influence of illicit drugs, alone and combined with alcohol has illustrated that particular driving parameters are affected by the consumption of particular drugs, and these effects can be moderated, synergistic, or additive when combined with alcohol. Alcohol and cannabis are two of the most commonly used psychoactive drugs, and are often used in combination. In Australia, alcohol and marijuana are also the two most prevalent drugs in the systems of drivers involved in accidents (Drummer et al., 2004). The combined effect of these two drugs upon driving is thus of particular concern, with the number of drivers being killed or injured with Δ9-tetrahydrocannabinol (THC) in their blood system increasing (Drummer et al., 2004), and the accident culpability of drivers increasing with the levels of THC in the blood and when detected in combination with alcohol (Drummer et al., 2004).

Studies examining the interactive effects of alcohol and THC have produced varied results concerning the additive or possibly synergistic effect of combining these drugs (Bramness et al., 2010). In controlled studies of cognitive performance and mood, the interaction between the drugs has demonstrated a mostly additive effect (Bramness et al., 2010; Liguori et al., 2002; Perez-Reyes et al., 1988; Ramaekers et al., 2004), although some evidence exists that at higher levels of both drugs, the effect may be synergistic (Lukas and Orozco, 2001). At lower doses of alcohol and THC, however, the interaction has recently been observed to be less than additive

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upon measures of cognitive performance, subjective experience and physiological response (Ballard and De Wit, 2011).

In specific regards to driving, driving performance has generally been found to be affected by THC and alcohol consumption in a dose-dependant manner. For THC consumption, these impairments have been observed to manifest across a range of factors related to safe driving including: reaction time; tracking; psychomotor skills; visual functions; and attention (Berghaus et al., 1995). Simulated and on-road driving studies report impaired perceptual processes, such as: monitoring the speedometer and maintaining speed; response to stimuli, such as stopping and starting; and other subsidiary tasks (Kelly et al., 2004; Ramaekers et al., 2004; Smiley, 1999). Tracking ability is the most consistently reported driving skill to be impaired after cannabis consumption which presents as an increase in the sideways movements of the vehicle and an increase in the percentage of time spent out of a lane (Papafotiou et al., 2005b; Ramaekers et al., 2000; Smiley, 1999). Alcohol consumption is well accepted to impair driving ability even at very low doses, and has wide ranging impairing effects upon; psychomotor skills, reaction time, perception, ability to keep the vehicle within traffic lanes, ability to focus on more than one task, vigilance, braking reaction time, speed control, increased aggression, and decreased hazard perception (Moskowitz and Fiorentino, 2000). Extant research concerning the combined effects of alcohol and THC consumption upon driving is so far inconclusive (Ronen et al., 2010), with issues concerning dosage levels of both drugs, tolerance and/or cross-tolerance of drugs, and the small sample sizes of previous studies possibly contributing to the inconsistencies in findings.

The suggestion that the effect of drug consumption on driving performance may be dependent on the individual's drug-use history has been supported by a number of findings. Infrequent users of THC have been observed to experience greater subjective feelings and greater sedative effects than frequent users of THC, when a high dose of THC (15 mg) was administered (Kirk and De Wit, 1999). When a lower dose THC (7.5 mg) was administered, however, frequent users reported higher ratings of subjective feelings than infrequent users. From these findings, the authors suggested that an individual's history of cannabis use may influence the subjective effects that are experienced after the consumption of cannabis and, in addition, the influence of the drug-use history may be dependent on the dose of drug that is administered. This finding may partly explain why the effects of THC consumption on driving performance have differed across studies. The findings of several studies have directly suggested that the effect of THC consumption on driving performance may be greater for non-regular users of THC than for regular users of THC (Marks and MacAvoy, 1989; Papafotiou, 2001; Wright and Terry, 2002).

Marks and MacAvoy observed that, when intoxicated by either cannabis and/or alcohol, cannabis users were less impaired in peripheral signal detection than were non-users, suggesting that regular cannabis users may develop a tolerance to the effects of cannabis and also a cross-tolerance to the effects of other drugs (Marks and MacAvoy, 1989). Wright and Terry (2002) also provided evidence to suggest that regular cannabis users may develop cross-tolerance to the effects of drugs and alcohol. They found that infrequent cannabis users were more impaired on a tracking task, following the consumption of a low dose of alcohol, than were chronic cannabis users. Given that the study investigated the effects of alcohol on tracking performance, the findings suggested that chronic cannabis use may lead to cross-tolerance to the effects of drugs including alcohol (Wright and Terry, 2002). Papafotiou (2001) reported that non-regular cannabis users, who had consumed cannabis, performed worse on a driving simulator task when compared to regular users. Non-regular users were involved in significantly more collisions and had slower reaction times to emergency situations after the consumption of THC (Papafotiou, 2001). The findings of Marks and MacAvoy (1989), Wright and Terry (2002) and Papafotiou (2001) indicate that driving-related psychomotor skills may be less impaired for regular THC users than for non-regular users, following the consumption of drugs and/or alcohol.

Recently, the impairing neurocognitive effects of cannabis have been demonstrated to be reduced in line with a 'tolerance' to THC in heavy THC users (Ramaekers et al., 2011). This reduced neurocognitive impairment in heavy THC users did not, however, translate further into a cross-tolerance to the impairing effects of alcohol (Ramaekers et al., 2011). With respect to driving whilst under the effect of both drugs, there has been some inconsistency in the findings from combined studies concerning the additive or synergistic effect of consumption of both substances together upon driving. The relative history of THC consumption by participants in these studies may have contributed to the inconsistent findings. For example, in a series of studies, Robbe (1998) noted that consuming THC alone had a mild and dose dependant (100, 200, and 300 μg/kg THC) impairing effect upon driving, but when combined with alcohol (BAC 0.04%), the lateral position variability in the road-tracking test and distance variability during deceleration manoeuvres in the car-following test were severely effected (Robbe, 1998). More recently, the combination of low dose alcohol (BAC = 0.04%) with THC (100 μg/kg and 200 μg/kg) indicated that the relatively low doses of alcohol or THC moderately impaired driving performance when given alone but severely impair driving performance in combination with a low dose of alcohol (Ramaekers et al., 2000). In contrast, Liguori et al. (2002) observed no additive effect when 0.25, or 0.5 g/kg alcohol and 1.75, or 3.33% THC were consumed together upon emergency braking latency.

Given that driving under the influence of alcohol and marijuana alone and in combination has been found to impair driving performance in controlled studies (Bramness et al., 2010) and are the most prevalent drugs in injured and deceased drivers (Drummer et al., 2004), further understanding of the interactive effects of these drugs upon driving is necessary. In light of previous studies concerning the effects of alcohol and THC upon driving, and the possible intervening effects of THC use, THC dose, and alcohol dose, the current study had two objectives: to examine the effects of cannabis and alcohol on driving performance at two doses; and to further identify if any differences between the effects of cannabis and alcohol on driving performance exist between regular cannabis users and non-regular cannabis users.

2. Methods

The project consisted of two separate studies, each comprising of six testing sessions combining two levels of THC administration with alcohol in two double-blind, placebo controlled trials. Each drug condition (alcohol and THC) was combined to comprise six sessions that are detailed in Table 1. In both studies, the order of administration of the sessions was counter-balanced.

2.1. Participants

The sample comprised 80 individuals; 31 female and 49 male. Age varied between 21 and 35 years ($M = 26.45$, $SD = 5$). Part one comprised 40 participants; 15 females and 25 males. Of these participants, 24 were regular cannabis users and 16 non-regular cannabis users as identified through a Frequency of Cannabis Use questionnaire. In part two, 40 participants included 16 females and 24 males. Of these participants, 24 were regular users, and 16 were non-regular cannabis users. All participants had smoked cannabis previously and underwent a medical examination prior to

Table 1
Experimental design.

Condition	Target BAC	THC dose
Low alcohol condition	0.00%	No THC
	0.00%	Low THC
	0.00%	High THC
	0.04%	No THC
	0.04%	Low THC
	0.04%	High THC
High alcohol condition	0.00%	No THC
	0.00%	Low THC
	0.00%	High THC
	0.06%	No THC
	0.06%	Low THC
	0.06%	High THC

participation to ensure that they had no: history of cardiac disorders; current or past substance abuse; mental health problems; allergies to drugs; and no other medical illness. All participants had a valid full driver's license (no probationary or learner drivers) to ensure that they had at least 3 years of driving experience. All participants provided informed consent, and the Institutional Research Ethics Committee approved the research (Table 2).

2.2. Drug conditions

Alcohol was administered according to a weight-related dose. The target blood alcohol concentration for participants in the low alcohol group was 0.04% BAC, and 0.06% BAC for participants in the high alcohol group. The placebo session was masked as being 0.04% BAC or 0.06% BAC when it was actually 0% BAC (nurse administered the breath alcohol test, the nurse did not administer any performance tests). By the time the driving task was performed, BAC had dropped to 0.03% and 0.05% respectively (required level for testing). The level of alcohol in blood drops approximately 0.01% every 40 min. The cannabis cigarettes used in the study were provided by the National Institute on Drug Abuse (NIDA) in the United States of America. Each THC cigarette was administered using a controlled smoking procedure (Papafotiou et al., 2005a). The two levels of THC administered were 1.8% THC for the low dose, and 3% THC for the high dose. A matching placebo cigarette (0% THC) was also utilised. The study was counter-balanced, double-blind, and used a within-subject design.

2.3. Driving simulator

The driving simulator was the CyberCAR LITE driver training and evaluation simulator (Thoroughbred Technologies Pty. Ltd.). The steering wheel, a 'Force Feedback', with integrated horn, indicators, headlights, ignition, automatic gears and hand brake, was affixed to a bench. The brake pedal and accelerator pedal were placed underneath the bench. Participants could adjust the pedal and seat position to suit their height. The simulator task was projected onto a 175 cm × 120 cm white screen (distance from steering wheel was 280 cm). Participants observed a two-dimensional computer-generated driving scene, as they would through a vehicle windscreen. The simulated dashboard, which was also projected onto the white screen, included a speedometer, rear-view mirror, and side-mirrors. The tasks administered employed a simulated conventional on-road light motor vehicle with automatic transmission. The driving simulator program consisted of two parts: the *Day-time* and *Night-time* driving modules. Each driving module (day and night) consisted of two tasks: 'freeway traffic driving' and 'city traffic driving'. Each scenario took approximately 5 min to complete. The complete driving module took approximately 20 min to complete. For the present study, a subset of 19 variables was analysed, each reflecting an error that can occur during the driving tasks (Stough et al., 2012). These variables reflect common errors (e.g., collisions, skidding, and straddling the barrier line), which are scored on a presence/occurrence basis; speeds at different moments during the simulation (e.g., initial speed on freeway) measured in kilometres per hour; and distances (e.g., following distance and stopping distance) measured in metres. Total 'Driving Impairment' and 'Signalling Impairment' scores are generated from summing variables related to driving or signalling respectively (Papafotiou et al., 2005b).

2.4. Blood samples

Blood samples were taken before the experimental sessions proceeded, to ensure that participants had no drugs in their system. Samples were analysed for the seven major drug classes (opiates, amphetamines, benzodiazepines, cannabinoids, barbiturates, cocaine and methadone). Two blood samples were taken during the 2.5-h testing period. One blood sample was taken at 20 min after completion of cannabis smoking (Time 1; pre-performance tests) and a second sample was taken at approximately 60 min after completion of cannabis smoking (Time 2; post-performance testing). A medical doctor was on call throughout the testing sessions. Each 10 ml blood sample was transported to a toxicology laboratory and analysed immediately. Blood samples were analysed for THC levels using the Gas Chromatograph–Mass Spectrometer (GC/MS) method. This method provides a means to confirm and quantify THC in both clinical and post-mortem specimens.

2.5. Procedure

On arrival, the participant was escorted to the Centre for Human Psychopharmacology, Swinburne University of Technology, where

Table 2
Blood alcohol and THC concentrations for pre- and post-driving assessments for each THC and alcohol condition.

Condition	THC pre-drive		THC post-drive		BAC pre-drive		BAC post-drive	
	Mean (ng/ml)	SD (ng/ml)	Mean (ng/ml)	SD (ng/ml)	Mean	SD	Mean	SD
Low alcohol condition								
Placebo Alc/Low THC	73.46	37.36	38.20	15.86	–	–	–	–
Placebo Alc/High THC	90.06	38.65	44.90	17.90	–	–	–	–
<0.05/Placebo THC	–	–	–	–	0.040	0.010	0.035	0.012
<0.05/Low THC	77.17	31.65	47.41	53.23	0.043	0.013	0.040	0.013
<0.05/High THC	119.94	69.92	53.66	22.85	0.037	0.012	0.035	0.015
High alcohol condition								
Placebo Alc/Low THC	69.25	30.36	38.07	16.71	.	.	.	.
Placebo Alc/High THC	92.14	50.80	47.92	22.99	.	.	.	.
>0.05/Placebo THC	.	.	.	.	0.080	0.018	0.074	0.018
>0.05/Low THC	75.99	38.52	39.55	15.31	0.070	0.019	0.070	0.015
>0.05/High THC	101.72	56.42	55.53	25.58	0.074	0.016	0.070	0.017

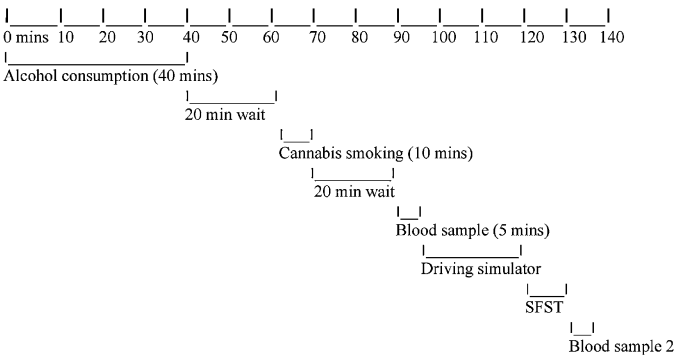

Fig. 1. Timeline for experimental sessions including alcohol consumption, waiting period before cannabis smoking, blood sampling and driving simulator performance.

the participant was given a beverage that contained either a quantity of vodka according to their body weight, mixed with the appropriate amount of orange juice or 200 ml orange juice. Once the drinks were consumed, participants waited 20 min, and then BAC was measured using a Lion Alcometer SD 400. If the target BAC was not reached, the participant was given another drink/s to bring their BAC up to the target level. Neither the investigator nor the participant viewed the BAC reading at any time (the nurse administered the breath alcohol test). Once target BAC was reached the participant was handed a cannabis cigarette which contained; 0% THC, 1.78% THC or 3.42% THC. Ten inhalations were completed and the cigarette was soaked and disposed of in a hazard waste bin. Participants waited 20 min before the first 10 ml blood sample was taken. Twenty minutes was used as past research indicates that although THC plasma levels peak immediately after smoking, behavioural impairment occurs once plasma levels have dropped (Moskowitz, 1985; Berghaus et al., 1995). Participants were then taken to the driving simulator to complete the driving module, this was followed by the SFSTs (results of which are presented elsewhere: Downey et al., 2012) and a final blood sample. A summary of an experimental session appear in Fig. 1.

2.6. Statistical analysis

The driving-simulator variables were analysed by repeated measures ANOVA using a $2 \times 2 \times 6$ mixed design Analysis of Variance (ANOVA). The between-subjects factors were Alcohol Dose (low: 0.03% BAC; high: 0.05% BAC) and THC use (regular or non-regular users) and the within-subject variables were the six experimental conditions. Where significant condition or interaction effects were observed, post hoc comparisons were undertaken to determine the significance of differences between the treatments. The statistical analyses were conducted using SPSS V18 for Windows.

3. Results

3.1. Blood analysis: the level of THC in plasma

Fig. 2 displays the mean level of active delta-9-THC in plasma for the low and the high cannabis conditions, with and without the administration of alcohol. The level of THC detected in plasma decreased over a 40 min period for each condition. In addition, the level of THC in plasma was higher after the administration of the High THC cigarette than the Low THC cigarette as expected. When alcohol was consumed prior to smoking the cannabis cigarette, the level of THC detected in plasma was generally higher. These results show a linear pattern between each drug condition, where the higher the THC dose consumed, the higher the level of THC in plasma, and when THC is consumed with alcohol the higher the level of THC in plasma. The level of THC in plasma for regular cannabis users and non-regular cannabis users was also examined, with the mean level of THC detected in plasma being higher in the regular cannabis users than non-regular users for each condition as seen in Fig. 2.

3.2. Driving performance

The driving data were analysed separately for the day-time and night-time driving scenarios. With regards to the overall impairment scores for driving and signalling for the six testing conditions and night or day simulations, a significant condition by THC use (whether participants were occasional or regular THC users) interaction was observed ($F_{5, 365} = 3.34$, $p < 0.01$). Post hoc comparisons revealed the interaction was due to regular THC users performing significantly worse in the alcohol alone condition ($p = 0.01$) and in the High THC condition ($p < 0.01$) in comparison to the non-regular users. A significant condition by THC use interaction was

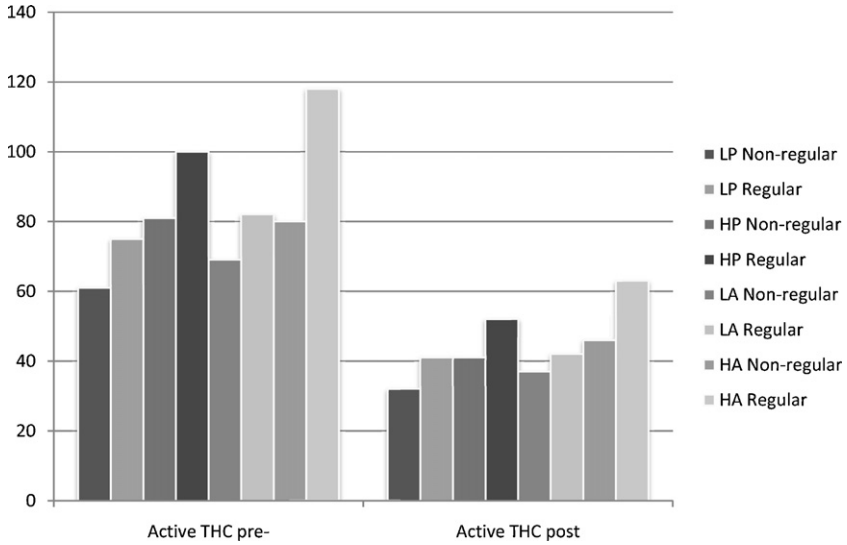

Fig. 2. The level of THC (ng/ml) in plasma for regular and non-regular cannabis users across the four active THC conditions. *Note*: *LP*, Low THC/placebo alcohol; *HP*, High THC/placebo alcohol; *LA*, Low THC/alcohol; and *HA*, High THC/alcohol.

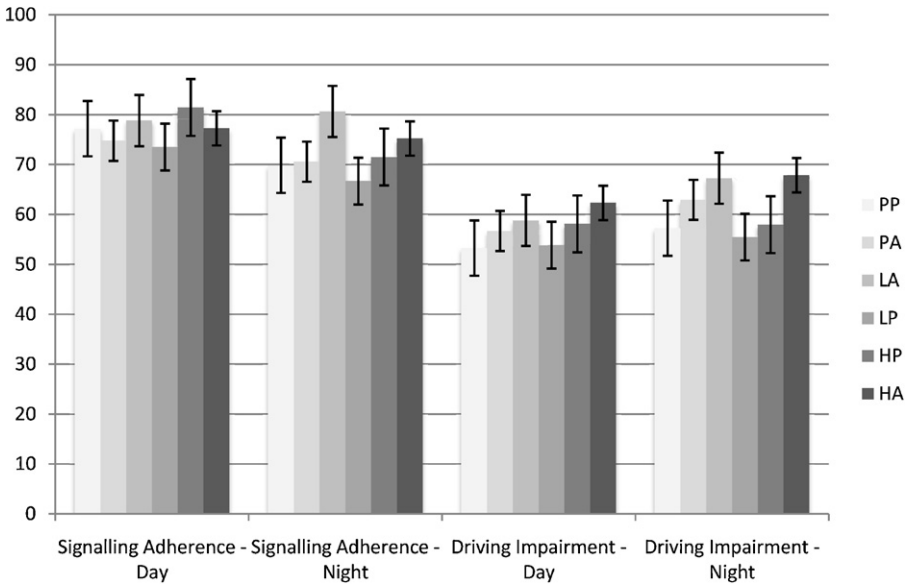

Fig. 3. Signalling adherence and driving impairment scores in the six experimental conditions for day and night-time driving simulations. *Note*. High THC/alcohol (HA); High THC/placebo alcohol (HP); Low THC/alcohol (LA); Low THC/placebo alcohol (LP); placebo THC/alcohol (PA); placebo THC/placebo alcohol (PP). Error bars are standard errors.

also detected for signalling adherence ($F_{5, 365} = 2.75$, $p = 0.02$), with the regular THC users producing significantly more signalling errors ($p = 0.01$) than the non-regular users in the High THC condition (Fig. 3).

For the night-time simulations, a significant effect for condition was observed for the signalling adherence scores ($F_{5, 370} = 2.24$, $p = 0.05$), interestingly, this effect was driven by the poorest performance by participants in the Low THC combined with alcohol condition, with performance in this condition being significantly worse than the placebo THC/placebo alcohol ($p = 0.03$), Low THC/placebo alcohol ($p < 0.01$), and placebo THC/alcohol conditions ($p = 0.03$). A significant effect for condition also occurred for overall driving impairment score ($F_{5, 370} = 3.56$, $p < 0.01$), with post hoc comparisons revealing significant performance differences between the placebo THC/placebo alcohol and the High THC/alcohol ($p < 0.01$) and Low THC/alcohol ($p < 0.01$) conditions. Participants also performed significantly better in the Low THC/placebo alcohol condition in comparison to the High THC/alcohol ($p = 0.01$) and Low THC/alcohol ($p = 0.01$). Performance in the High THC/alcohol condition was also observed to be significantly worse than in the High THC/placebo alcohol condition ($p < 0.05$). Together, these results for the day and night simulations suggest that overall driving and signalling performance is impaired by the combination of alcohol and THC at different doses, but it may be more informative to examine individual driving parameters to identify what, if any specific driving indices are differentially affected by this drug combination (Stough et al., 2012).

Descriptive statistics of the individual driving indicators appear in Table 3 for the day-time and Table 4 for the night-time simulations with examination of the effect of condition and interactions

Table 3
Driving simulator variables for day simulations for each treatment condition.

	Placebo–placebo	Placebo–alcohol	Low THC–alcohol	Low THC–placebo	High THC–placebo	High THC–alcohol
Collision	4.00 ± 7.56	4.81 ± 7.98	3.54 ± 5.32	4.63 ± 7.45	5.25 ± 9.00	4.88 ± 7.46
Skidding	0.29 ± 0.90	0.58 ± 1.90	0.38 ± 1.20	0.20 ± 0.49	0.15 ± 0.48	0.40 ± 1.33
Intersection – wheels not straight	0.34 ± 0.95	0.34 ± 1.07	0.30 ± 1.03	0.41 ± 1.33	0.64 ± 1.41	0.60 ± 1.54
Waited too long before moving off	0.39 ± 0.67	0.38 ± 0.63	0.30 ± 0.56	0.38 ± 0.60	0.44 ± 0.78	0.33 ± 0.65
Inappropriate braking	4.73 ± 5.48	5.27 ± 6.64	6.08 ± 6.80	5.63 ± 6.58	5.40 ± 5.60	5.75 ± 5.84
Driving too fast	0.88 ± 2.36	2.03 ± 4.90	1.01 ± 2.32	1.69 ± 3.97	1.19 ± 2.78	1.63 ± 4.04
Unsafe Following Distance[c]	25.31 ± 14.91	25.25 ± 20.68	28.61 ± 19.00	22.88 ± 15.83	26.25 ± 16.64	28.81 ± 17.69
Driving too slow	1.76 ± 0.86	1.65 ± 0.92	1.71 ± 1.25	1.53 ± 0.93	1.68 ± 1.10	1.68 ± 1.10
Steering Straddle Barrier Line	0.65 ± 1.68	0.94 ± 1.92	1.37 ± 3.21	1.08 ± 1.93	0.95 ± 1.65	1.08 ± 1.83
Not leaving sufficient clear space when stopping	0.38 ± 0.91	0.35 ± 0.89	0.73 ± 1.40	0.45 ± 1.19	0.48 ± 0.91	0.68 ± 1.31
Stopping unnecessary/needless	1.00 ± 1.22	0.89 ± 1.34	0.84 ± 1.10	0.81 ± 1.13	0.83 ± 1.08	0.85 ± 1.20
Violation Traffic Law red light	2.00 ± 4.03	1.65 ± 4.92	2.41 ± 5.82	3.50 ± 8.73	2.75 ± 6.56	2.88 ± 6.79
Violation Traffic Law Solid Line	0.55 ± 1.59	1.16 ± 1.86	0.80 ± 1.41	0.91 ± 1.79	0.90 ± 2.08	1.09 ± 1.93
Violation Traffic Law Speed Limit	5.83 ± 5.81	6.61 ± 7.38	5.82 ± 6.29	5.00 ± 5.47	4.70 ± 5.48	5.95 ± 5.90
Initial Speed Freeway[cu]	97.06 ± 30.03	95.35 ± 34.22	85.79 ± 39.71	84.52 ± 39.07	87.23 ± 38.88	88.40 ± 40.75
Initial Speed City	32.38 ± 18.49	36.19 ± 20.37	33.89 ± 19.23	39.75 ± 17.62	32.51 ± 20.07	35.44 ± 18.95
Reaction Time to Emergencies[cu]	18.69 ± 5.87	18.69 ± 5.11	18.65 ± 4.74	17.61 ± 6.65	18.36 ± 7.19	18.71 ± 6.41
Stopping Distance Freeway	110.94 ± 41.42	114.29 ± 38.26	105.14 ± 40.09	101.81 ± 31.99	113.65 ± 38.08	113.08 ± 42.33
Stopping Distance City	24.64 ± 11.13	28.91 ± 18.78	27.25 ± 13.30	28.22 ± 10.77	26.35 ± 15.42	27.98 ± 12.54
Total: signalling adherence	77.18 ± 32.29	74.77 ± 40.89	78.82 ± 34.05	73.51 ± 32.15	81.43 ± 41.55	77.26 ± 30.57
Total: driving impairment	53.25 ± 27.90	56.67 ± 40.23	58.80 ± 33.62	53.83 ± 35.17	58.11 ± 32.24	62.30 ± 33.58

Note. [c] denotes a significant effect of condition, [cu] denotes a significant interaction of condition and use; [c] Speed control following distance – $F_{(5, 370)} = 2.30$, $p < 0.05$; [cu] $F_{(5, 370)} = 2.61$, $p < 0.05$; Initial Speed Freeway – [cu] $F_{(5, 370)} = 2.61$, $p < 0.05$; reaction time combined – [cu] $F_{(5, 335)} = 3.85$, $p < 0.01$.

Table 4
Driving simulator variables for night simulations for each treatment condition.

	Placebo–placebo	Placebo–alcohol	Low THC–alcohol	Low THC–placebo	High THC–placebo	High THC–alcohol
Collision	3.63 ± 6.01	5.06 ± 6.38	7.09 ± 8.34	4.63 ± 7.11	5.50 ± 8.70	6.25 ± 7.36
Skidding	0.25 ± 0.56	0.32 ± 0.82	0.33 ± 1.03	0.23 ± 0.71	0.09 ± 0.36	0.36 ± 0.82
Intersection – wheels not straight	0.34 ± 0.95	0.49 ± 1.12	0.57 ± 1.37	0.79 ± 1.70	0.60 ± 1.30	0.49 ± 1.11
Waited too long before moving off[cu]	0.31 ± 0.70	0.42 ± 0.71	0.27 ± 0.50	0.39 ± 0.67	0.44 ± 0.74	0.30 ± 0.58
Inappropriate braking	5.93 ± 6.88	6.22 ± 6.88	6.76 ± 6.72	6.09 ± 7.32	6.18 ± 7.78	6.25 ± 5.70
Driving too fast[c,cd]	1.13 ± 3.47	0.70 ± 2.86	1.33 ± 2.74	2.06 ± 4.19	0.69 ± 2.07	2.38 ± 4.36
Unsafe Following Distance	28.44 ± 16.81	31.20 ± 21.05	30.44 ± 19.48	25.49 ± 18.06	27.94 ± 17.51	31.69 ± 21.32
Driving too slow	1.76 ± 1.01	1.70 ± 1.10	1.59 ± 1.14	1.54 ± 0.97	1.26 ± 0.94	1.50 ± 0.91
Straddling Barrier Line[c,cu]	0.65 ± 1.45	0.91 ± 1.81	1.90 ± 3.02	1.05 ± 2.29	1.48 ± 2.15	1.60 ± 2.71
Not leaving sufficient clear space when stopping[c]	0.30 ± 0.72	0.38 ± 0.91	0.48 ± 0.97	0.18 ± 0.57	0.35 ± 0.83	0.75 ± 1.44
Stopping unnecessary/needless	0.78 ± 0.81	0.94 ± 0.99	0.94 ± 1.11	0.86 ± 1.05	0.65 ± 0.83	0.93 ± 0.94
Violation Traffic Law red light	1.88 ± 4.24	2.03 ± 6.86	2.03 ± 5.40	1.63 ± 4.89	1.25 ± 3.69	1.38 ± 4.13
Violation Traffic Law Solid Line[c]	0.55 ± 1.27	0.38 ± 0.96	0.71 ± 1.54	0.68 ± 1.35	0.80 ± 1.37	1.13 ± 1.91
Violation Traffic Law Speed Limit[c]	6.45 ± 6.34	6.30 ± 7.15	6.76 ± 7.33	5.13 ± 6.22	4.83 ± 5.43	6.30 ± 6.29
Initial Speed Freeway	93.60 ± 31.83	91.29 ± 33.10	84.84 ± 39.45	87.33 ± 34.02	78.17 ± 41.45	86.46 ± 37.30
Initial Speed City	34.97 ± 18.36	34.29 ± 18.52	35.00 ± 19.20	36.37 ± 18.93	34.86 ± 18.42	32.29 ± 19.64
Reaction Time to Emergencies	17.59 ± 4.30	19.14 ± 3.59	19.44 ± 4.89	18.63 ± 5.40	17.54 ± 6.82	18.79 ± 4.96
Stopping Distance Freeway	107.34 ± 39.77	110.51 ± 36.90	107.32 ± 37.93	100.25 ± 37.91	95.52 ± 32.43	97.66 ± 34.78
Stopping Distance City	26.01 ± 11.06	22.06 ± 10.65	25.72 ± 13.49	27.05 ± 12.87	25.40 ± 13.49	24.18 ± 13.16
Total: signalling adherence	69.84 ± 29.93	70.56 ± 31.09	80.62 ± 40.76	66.68 ± 30.63	71.50 ± 32.43	75.21 ± 31.44
Total: driving impairment	57.24 ± 32.07	62.92 ± 39.81	67.27 ± 35.15	55.46 ± 35.30	57.95 ± 33.26	67.85 ± 38.02

Note: [c] denotes a significant effect of condition, [cu] denotes a significant interaction of condition and use, [cd] denotes a significant interaction between condition and alcohol dose; [cu] Waited too long before moving off – $F_{(5, 370)} = 2.58$, $p < 0.05$; [c] Speed control fast – $F_{(5, 370)} = 3.56$, $p < 0.01$; [cd] Speed control fast – $F_{(5, 370)} = 2.38$, $p < 0.05$; [c] Steering Straddle – $F_{(5, 370)} = 5.00$, $p < 0.01$; [cu] Steering Straddle – $F_{(5, 370)} = 2.23$, $p = 0.05$; [c] Stopping clear space – $F_{(5, 370)} = 4.46$, $p < 0.01$; [c] Violation Traffic Law Solid Line – $F_{(5, 370)} = 2.48$, $p < 0.05$; [c] Violation Traffic Law Speed Limit $F_{(5, 370)} = 2.48$, $p < 0.05$.

appearing the notes below each table. Post hoc analysis of the significant condition and interaction effects indicated that the effect of condition on Unsafe Following Distance was due to day-time performance being significantly different between the placebo alcohol/placebo THC condition and High THC/alcohol condition ($p < 0.05$); performance in the Low THC/placebo alcohol condition was also significantly better than the High THC/alcohol ($p < 0.01$) and High THC/placebo alcohol ($p < 0.02$) conditions. The scores for initial speed when entering the freeway produced a significant interaction between condition and user level, with regular THC users entering the freeway at significantly higher speeds in the placebo alcohol/High THC ($p < 0.01$), alcohol/Low THC ($p < 0.05$) and alcohol/High THC ($p < 0.01$) conditions. A significant condition by user interaction was also detected for reaction time, with significantly faster reaction times to emergencies occurring in the placebo alcohol/High THC condition for the non-regular users ($p < 0.01$).

For the night-time simulations, a significant condition by user interaction was detected for waiting too long to move off, with non-regular users producing this error more often in the alcohol/placebo THC condition ($p < 0.05$). For the driving indicator, Driving too fast, significant effect of condition ($p < 0.01$) and a significant interaction between condition and alcohol dosage ($p < 0.05$) were observed. Post hoc examination of the condition effect showed that performance was significantly better in the Low THC/placebo alcohol in comparison to the High THC/placebo alcohol ($p < 0.05$) and placebo THC/alcohol ($p < 0.05$) conditions. Performance in the High THC/alcohol condition was also significantly worse than in the High THC/placebo alcohol ($p < 0.05$) and placebo THC/alcohol ($p < 0.05$) conditions. The interaction between alcohol dose and condition was driven by poorer performance in the Low THC/placebo alcohol condition by participants in the low alcohol study ($p = 0.01$).

A large effect of condition was also evident for Steering Straddling (straddling the lane dividing lines), with performance being significantly worse in the High THC/placebo alcohol ($p < 0.01$), Low THC/alcohol ($p < 0.01$), High THC/alcohol ($p < 0.01$) conditions in comparison to the placebo THC/placebo alcohol condition. More line straddling also occurred in the Low THC/alcohol condition than when the Low THC dose was not administered with an active dose of alcohol ($p < 0.05$). A greater amount of straddling also occurred in the High THC/placebo alcohol condition in comparison to the placebo THC/alcohol condition ($p < 0.05$). The consumption of both doses of THC in combination with alcohol ($p < 0.05$) also produced significantly more straddling errors than alcohol and placebo THC. Differences were also apparent between conditions for leaving adequate space when bringing the car to a stop, with significantly greater space being left in the High THC/alcohol condition than all the conditions ($p < 0.05$) other than the Low THC/alcohol condition. A significant difference also occurred between the Low THC/placebo alcohol and Low THC/alcohol conditions, with less space being left when active THC and alcohol were combined ($p < 0.05$).

A main effect for condition was observed for drivers committing the Violation of Traffic Law, crossing the solid line, significantly more often in the High THC/alcohol condition in comparison to the placebo THC/placebo alcohol, placebo THC/alcohol, and Low THC/alcohol conditions ($p < 0.05$). Significantly more violations also occurred in the High THC/placebo alcohol condition in contrast to the placebo THC/alcohol condition. A significant main effect of condition was also noted for Violating the Speed Limit, with post hoc comparisons revealing this difference being due to more violations occurring in the placebo THC/placebo alcohol, Low THC/alcohol, and High THC/alcohol conditions in comparison to the High THC/placebo alcohol condition. A significant difference also existed between the Low THC/placebo alcohol and Low THC/alcohol conditions, with the active alcohol condition producing more speeding violations ($p < 0.05$).

4. Discussion

The present study found that driving simulator performance was significantly compromised in the THC and alcohol combined conditions, particularly in the night-time simulations. The addition of alcohol to both the low and high doses of THC produced an additive decrement in driving impairment scores of 21% and 17% for the low and High THC conditions respectively. Generally, regular cannabis users displayed more driving errors than non-regular

cannabis users in contrast to expectations. In addition to impairing driving performance generally, a number of driving specific indices were differentially identified as being affected by alcohol and THC, some of which were more affected during the combined conditions. These specific indicators provide explicit evidence of the types of driving behaviours and abilities that are compromised in drivers affected by THC alone, and in combination with varying levels of alcohol. The blood results of the present study are consistent with past research showing that the level of THC detected in the blood is higher after the consumption of THC in combination with alcohol, than THC without alcohol (Lukas and Orozco, 2001). Regular users showed higher levels of THC in plasma than non-regular users, and the higher the dose of THC administered, the higher the level of THC detected in plasma.

Differences between the six experimental conditions were observed on a number of individual driving indices. Participants' ability to control the speed of their vehicle and maintain a safe distance was differentially affected by the conditions with the placebo THC and Low THC with no alcohol conditions driving closer to cars in front that in the High THC and alcohol condition; with this closer driving not producing significantly more collisions, skidding or inappropriate braking in comparison to the other conditions. Participants also drove closer in the Low THC and no alcohol condition than in the High THC without alcohol condition, suggesting the increase in THC dosage alone influences perception of what is a safe distance to leave between cars when affected by THC; given the addition of alcohol in the placebo THC conditions did not affect the following distance driven at by participants. This result possibly reflects drivers' compensation for slowed reaction times and reduced perceptual abilities (Berghaus et al., 1995) associated with THC consumption.

Further to this, differences in amount of 'straddling the solid line', 'straddling the barrier line', 'insufficient stopping clear space' occurred was higher when THC was consumed than when placebo THC was consumed (with or without alcohol). This suggests that there is an increased likelihood that individuals who have consumed cannabis drive with two or more wheels of the vehicle moving over lines marked out for traffic moving in the same direction, or lines marked out for traffic moving in the opposite direction. In addition, there is an increased likelihood that individuals who have smoked cannabis will drive with greater clear space between their own vehicle and the vehicle in front of them in an effort to compensate for their poorer vehicle control. Although the consumption of THC was also associated with slower initial speed when entering the freeway, this did not also appear to be related to safer driving. The observation of an increase in straddling barrier and solid lines during the THC condition indicates that driving slowly (at one point or another) is associated with deficiencies in abilities essential to safely drive a motor vehicle. The results also highlight that, when under the influence of THC, many driving errors are observed whether alcohol is also consumed or not. The findings of the present study are almost identical to those reported in a previous project by our research team utilising the same driving simulator (Papafotiou et al., 2005b), where consumption of THC was associated with an increase in 'straddling the solid line' and 'straddling the barrier line'. These findings are consistent with previous research reporting that THC impairs car control (Moskowitz, 1985), increases the standard deviation of the lateral position of a vehicle (Smiley et al., 1981; Ramaekers et al., 2000), impairs tracking ability (Ramaekers et al., 2000) and increases the number of sideway movements of a vehicle and percentage of time spent out of a lane (Robbe and O'Hanlon, 1999; Ramaekers et al., 2000).

With respect to impairment associated with the administration of alcohol (with and without THC), errors involving driving at an appropriate speed were significantly increased with the addition of alcohol in the High and Low THC conditions. A similar increase in errors for violations of the speed limit also occurred with the addition of alcohol in the High THC condition (with the Low THC condition increasing by a similar magnitude, but not statistically significant). The results are consistent with previous research that has reported that alcohol increases the number of errors in variables that measure acceleration, braking, and speeding (Crancer et al., 1969; Krueger and Vollrath, 2000; Stein et al., 1983).

Performance on the driving simulator also produced a number of significant differences between regular cannabis users and non-regular cannabis users. Overall, regular users produced more signalling errors and greater driving impairment in the High THC condition, and also were more impaired than non-regular users in the alcohol alone condition. Regular users produced faster initial speeds entering the freeway when influenced by both doses of THC and alcohol, as well as when affected by the High THC dose alone. Non-regular users also took longer to take off from a stationary (red light/stop sign) than regular users in the alcohol alone condition, but produced faster reaction times in the High THC condition to stimuli, suggesting a more cautious approach to the driving simulations. These results are somewhat inconsistent with previous research where regular users perform better than non-regular users (Marks and MacAvoy, 1989; Wright and Terry, 2002). Since regular users are more experienced with the psychological and physiological effects of THC, it has been suggested that these users are better able to compensate for the impairing effects of the drug. In the present study, the addition of alcohol may have influenced driving behaviour differently in both groups. For instance, in the THC condition, regular users performed significantly worse than non-regular users with and without alcohol. In the present study, the consumption of alcohol – which has previously been associated with over-confident driving behaviour, decreased inhibitions and greater risk taking – may have led regular users to underestimate the effects of consuming THC with alcohol. These conflicting findings suggest that research in this area remains equivocal and further investigation is required.

It should also be noted that the degree of impairment in the overall driving and signalling measures was subtle, and that some of the individual driving simulator variables were relatively unaffected by the various THC/alcohol conditions. The analysis of the multiple outcome measures did not include an adjustment for multiple comparisons, due to the exploratory nature of the study's aims to explore a wide variety of driving related actions and behaviours. Future research into the interactive effects of alcohol and THC upon driving should consider examining the more salient aspects of driving impairment attributable to alcohol and illicit drug intoxication (e.g., standard deviation of lane positioning).

5. Conclusion

With the number of driving under the influence of drug related accidents and deaths increasing worldwide, understanding of the impairing effects of individual drugs, and combinations of drugs upon driving skills and behaviour is necessary to educate regular or occasional drug-using drivers about the dangers this behaviour presents to themselves, and those they share the road with. THC is generally considered to be a 'soft' illicit drug, and occasional and regular users report to be willing to drive even when under the effect of THC alone, and in combination with alcohol (Ronen et al., 2010). The current study illustrates how THC and alcohol (even at legal driving levels) negatively affect driving ability individually, and more so in combination in a double-blind, placebo-controlled driving simulation study. That these drugs impair driving ability in both regular and non-regular THC users under controlled conditions, further validate the strong legal measures currently

being enforced within Victoria, Australia (Boorman and Owens, 2009), where drivers producing a legal roadside breathalyser reading (<BAC 0.05) can be assessed for the presence of THC, MDMA and other amphetamines known to effect driving (Silber et al., 2005; Stough et al., 2011) via salvia sampling.

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