Self-regulation of driving behavior under the influence of cannabis: the role of driving complexity and driver vision

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Abstract

Objective: This study analyzed the self-regulation behaviors of drivers under the influence of cannabis and its relationship with road complexity and some driver traits, including visual deterioration.

Background: Cannabis is the illicit drug most often detected in drivers; its use results in significant negative effects in terms of visual function. Self-regulation behaviors involve the mechanisms used by drivers to maintain or reduce the risk resulting from different circumstances or the driving environment.

Methods: Thirty-one young, occasional cannabis users were assessed both in a baseline session and after smoking cannabis. We evaluated the visual function (visual acuity and contrast sensitivity) and driver self-regulation variables of both longitudinal and lateral control as the speed adaptation and standard deviation of lateral position (SDLP).

Results: Visual function was significantly impaired after cannabis use. Recreational cannabis use did not result in self-regulation, although some road features such as curved roads did determine self-regulation. Male participants adopted mean faster driving speeds with respect to the speed limit. Driver age also determined better lateral control with lower SDLPs. In addition, visual impairment resulting from cannabis use (contrast sensitivity) was linked with self-regulation by changes in longitudinal and lateral control.

Conclusion: Contrast sensitivity could be a good indicator of individual visual status to help determine how drivers self-regulate their driving both in normal conditions and while under the influence of cannabis.

Application: The findings provide new insights about driver self-regulation under cannabis effects and are useful for policy making and awareness campaigns.

Keywords: cannabis, THC, driver self-regulation, vision, contrast sensitivity

Précis:

Cannabis is the illicit drug most often detected in drivers. This study shows how visual function is significantly deteriorated after cannabis use. Smoking cannabis did not cause drivers to self-regulate their behaviors. However, road traffic complexity, visual function impairment, age and gender were related to driver self-regulation.

INTRODUCTION

Driving under the influence of cannabis (DUIC) is a growing concern in terms of road safety. Over the past decade, the number of cannabis users who drive a car following cannabis consumption has increased worldwide (Azofeifa et al., 2019; Baldock & Lindsay, 2020; Brown et al., 2019; Davey et al., 2020; Domingo-Salvany et al., 2017; Robertson et al., 2017). The main psychoactive substance found in cannabis is THC (Δ9-tetrahydrocannabinol), which results in impairment of the cognitive and psychomotor functions required for driving. It is generally well-established that cannabis impairs some cognitive functions including attention, reaction time, coordination, planning, and capacity for decision-making (Bondallaz et al., 2016; Meier et al., 2012; Solowij & Battisti, 2008). Cannabis use has also been shown to alter visual function (Ortiz-Peregrina et al., 2021; Ortiz-Peregrina, Ortiz, Castro-Torres, et al., 2020), in other words, the mechanism through which individuals get nearly 90% of all the information they need to drive (Wood, 2019). Moreover, this alteration has been demonstrated for several different visual capacities such as visual acuity (VA), contrast sensitivity, stereoacuity, accommodation accuracy, halo perception, straylight, and glare sensitivity (Ortiz-Peregrina et al., 2021; Ortiz-Peregrina, Ortiz, Castro-Torres, et al., 2020).

Visual acuity is the most widely employed visual test for licensing purposes (Bron et al., 2010). Impaired VA can result in difficulties related to obstacle detection and traffic sign legibility (Higgins et al., 1998; Higgins & Wood, 2005; Ortiz-Peregrina, Ortiz, Casares-López, et al., 2020). However, the negative effects of cannabis use are also noticeable in terms of the contrast sensitivity function (Lalanne et al., 2017; Mikulskaya & Martin, 2018; Ortiz-Peregrina et al., 2021; Ortiz-Peregrina, Ortiz, Castro-Torres, et al., 2020). Although contrast sensitivity does not form part of standardized driver visual assessment tests (Bron et al., 2010), its importance for driving performance and safety risk has been highlighted (Owsley & Mcgwin, 2010). Owsley et al., (2001) found that impaired contrast sensitivity is an important risk factor for traffic accidents in drivers with cataracts. Additionally, several studies have concluded that this visual test can be a good predictor of driving performance (Wood, 2002; Wood & Owens, 2005). These visual parameters were also included in the study by Ortiz-Peregrina et al., (2020). The authors studied a sample of 20 young cannabis users and analyzed the influence of this drug in driving performance and visual function. The results demonstrated that cannabis consumption generated an impairment in visual parameters such as contrast sensitivity, visual acuity or stereoacuity and that drivers under the influence of cannabis had poorer driving performance in a simulator compared to the baseline condition. Moreover, the study found significant correlations between poorer VA, contrast sensitivity, or stereoacuity, and a decreased capacity for maintaining the car within the lane. This result is in agreement with previous studies (Ortiz-Peregrina, Ortiz, Salas, et al., 2020; Ortiz et al., 2018; Szlyk et al., 1995) and suggests that these visual parameters are good estimators of the visual input required for vehicle’s lateral control. Cannabis could deteriorate visual guidance abilities, affecting the detection of visual cues on the road, for example the road marks that limit the lane.

Previous research has demonstrated that cannabis impairs driving performance, resulting in a reduced mean speed and headway distance and increased lane position, steering wheel position, and reaction time variability (Alvarez et al., 2021; Ortiz-Peregrina, Ortiz, Castro-Torres, et al., 2020). Regarding the crash risk of DUIC, several studies have found contradictory results. Two meta-analyses concluded that cannabis doubled the risk of crashing (Asbridge et al., 2012; Li et al., 2012) and a later publication concluded that cannabis use increased the crash risk from a low to medium magnitude (Rogeberg & Elvik, 2016). However, in contrast, a subsequent meta-analysis concluded that DUIC was not significantly linked with unfavorable traffic events, defined as collisions, injury, or death (Hostiuc et al., 2018). In the same line, the recent meta-analysis by Rogeberg (2019) concluded that the risk of crashing was only minimally increased among THC-positive drivers.

The risk of crashing is a function of the demands of the road environment, the car, the driver's abilities, and human factors (Fuller et al., 2008). Driver self-regulation comprises the compensatory strategies or behaviors adopted to compensate for risk. If an individual finds driving more demanding because of a decline in some of the functions required to carry out this task (e.g., cognitive, motor, or sensorial functions), they can self-regulate their behavior to try to drive more safely to compensate for the impairment (Onate-Vega et al., 2020). Generally, self-regulation has been thought of as a coping strategy that older drivers apply when recognize functional impairments (Agramunt et al., 2017; Ball et al., 1998). However, driver self-regulation can be also present in other circumstances such as when performing secondary task while driving (e.g. mobile phone interactions; Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020; Oviedo-Trespalacios et al., 2017a), or when the driver has a transitory decline in their capacity due to fatigue, sleep deprivation or drug use. Then, when a driver is under the effects of cannabis, s/he can self-regulate at different levels, including strategic control (e.g. avoiding certain situations such as nighttime driving or in bad weather conditions), tactical control (e.g., regulating the timing of when they DUIC or by looking for an easier route), and operational control (e.g., over-correcting the vehicle's position or reducing their speed to well under the limit; Molnar et al., 2014; Oviedo-Trespalacios et al., 2017b). An important consideration is that an increase in SDLP could be interpreted as an impairment or overcorrection by the driver (Oscar Oviedo-Trespalacios et al., 2018), so caution is needed when interpreting the results. Over-correcting the vehicle's position manifests in higher standard deviation of the lateral position (SDLP), and if the driver is losing control of the vehicle a lack of overcorrection could result in lane departures/crashes. Generally, one of the most commonly reported effects of this drug on driving is an increase in SDPL (Micallef et al., 2018; Ramaekers et al., 2000). In addition, numerous articles have reported that drivers under the influence of cannabis usually select lower speeds (Alvarez et al., 2021).

As stated above, the risk of crashing depends on the environment demands. When drivers find some road traffic environments to be more difficult, they initiate self-regulation behaviors to maintain an adequate level of safety and reduce the increased risk imposed by the environmental demands (Fuller et al., 2008). For example, a visually cluttered urban area can be perceived as difficult for a driver, who can adapt their driving by reducing the speed in order to gain time to integrate all the necessary visual information (traffic lights, signals, pedestrians, billboards, etc.). It is important to consider that the driving environment is dynamic, and this requires drivers to continuously monitor environment-related hazards and, consequently, to self-regulate their behavior during the driving task. Previous research in distracted drivers has shown that drivers adapt their behavior when facing more complex situations such as driving along winding and narrow roads at high speed, or when using roads with more traffic interactions. When faced with these situations, these drivers usually reduce their speed and increase their lateral lane position variability (Liu & Ou, 2011; Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020; Oviedo-Trespalacios et al., 2017a; Tractinsky et al., 2013). Driver characteristics such as age, gender or personality traits can also contribute to adapting driving behavior. Drivers with higher frequency of DUIC generally present a risky driving style, including reckless on-road behaviors such as speeding (Bédard et al., 2007; Bergeron & Paquette, 2014). In addition, previous research suggest that DUIC is associated with demographics such as gender and age, with young males being more likely to drive under the influence of cannabis (Jones et al., 2007; Richer & Bergeron, 2009). The fact that younger males are more prone to drive under the influence of cannabis suggests that they have less awareness and underestimate the risks. Thus, young male drivers could adapt less their behavior when DUIC, for example, driving at similar speeds than in normal conditions. Hence, demographics and other psychosocial factors could cause drivers to adapt their driving differently when under the effects of cannabis.

Thus, the aim of this study was to analyze the self-regulation behaviors of drivers under the influence of cannabis. Self-regulation is an important set of behaviors for road safety because it can have a protective impact against risk (Choudhary & Velaga, 2017; Li et al., 2019). In this work, we studied the influence of certain road characteristics as well as some driver traits. Among the latter, we used visual deterioration following cannabis use as a measure of the physical consequences of cannabis consumption. This decline in a physical capacity important for driving could lead drivers to adopt strategies (e.g. speed reduction) to try to reduce or maintain the perceived risk at an acceptable level with which they feel safe behind the wheel.

METHODS

Participants

This research was conducted in accordance with the Declaration of Helsinki and was prospectively approved by the University of Granada Human Research Ethics Committee (921/CCEIH/2019). A signed informed consent was obtained from each participant prior to enrolling in the study. Thirty-one volunteers who were cannabis users (20 males and 11 females), with a mean age of 23.4 ± 5.1 years, were included in this work. Participants were current users, (i.e. self-reported cannabis use of at least once in the 3 months prior) and they were regular drivers, defined as driving at least once a week. Individuals were excluded from the study if they had any history of other drug use (i.e., more than 5 times in their lifetime), non-normal corrected vision, binocular problems, a history of ocular surgery or medical disease, or if they showed signs of alcohol use disorders.

To evaluate this latter aspect, the Alcohol Disorders Identification Test (AUDIT) (Babor et al., 2001) was administered. The use of cannabis was also evaluated through the Cannabis Disorders Identification test revised (CUDIT-r) (Adamson et al., 2010). These test scores allowed us to quantify how frequent or hazardous the use of the substance was in these participants by identifying possible disorders. Table 1 includes the description of self-reported information about the participant's demographics, consumer profile, and driving habits, while Figure 1 shows the frequency of DUIC reported by the participants.

TABLE 1. Demographic data, consumption profile, and driving habits of the sample.

Parameter	**Mean ± *SD* / %**
Age (years)	23.42 ± 5.12
Gender (%)	
Males	64.52
Females	35.48
Monthly consumption (number of days)	10.60 ± 10.80
Age of onset (years)	17.06 ± 1.91
Number of years of consumption (years)	5.81 ± 4.95
CUDIT-r score	8.84 ± 5.56

Continuous variables are shown as the mean ± *SD* and categorical variables are shown as percentages.

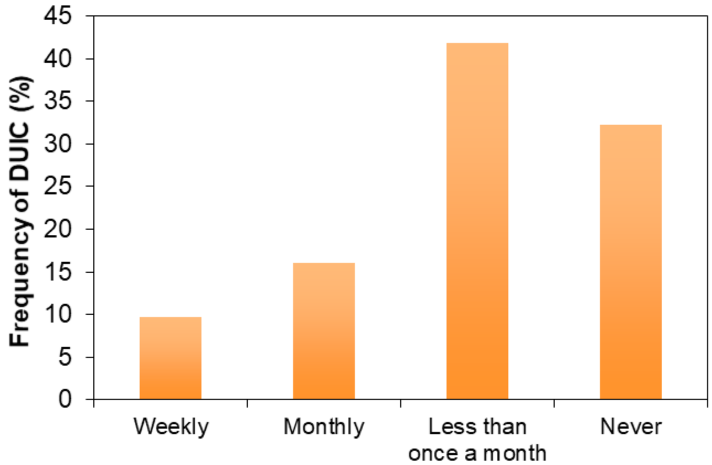

Figure 1. The frequency of driving under the influence of cannabis reported by the study participants.

Experimental procedure

At their initial visit to the laboratory, the participants were informed about the study and were given the informed consent to read and sign. Once the driving simulator training protocol was complete (more details are provided below), two experimental sessions were carried out at least one week apart to avoid learning effects: one involving no substance use and the other 20 minutes after smoking a cannabis cigarette, ensuring that "high" was noted (Grotenhermen, 2003). Each session comprised several visual tests and the driving simulator route (in a random order) and lasted about 75 minutes. Experimental sessions of this length allowed us to guarantee that the cannabis use had a considerable psychoactive effect during the session because its effect tappers off within 2–3 hours (Grotenhermen, 2003). The order of the sessions (baseline and after smoking cannabis) was randomly selected, with the number of subjects and test performed being the same for each session.

The participants made the cannabis cigarette as they usually do for their habitual consumption, thus simulating realistic use. Before the experimental sessions, the participants abstained from alcohol use for 24 hours and from cannabis use for 4 days. To obtain an objective drug-intake screening during the sessions, a saliva drug test (Dräger DrugTest 5000) was performed. This device allowed us to ensure that no other substances had been used (amphetamines, benzodiazepines, cocaine, methamphetamines, opiates, methadone, or ketamine). For cannabis, the Dräger test is able to detect concentrations higher than 12ng/ml up to 8-14 hours after consumption. For alcohol screening, the participants' breath alcohol content (BrAC) was measured with a Dräger Alcotest 7110 MK-III (Dräger Safety AG & Co. KGaA. Lübeck, Germany).

Visual function assessment

Visual acuity evaluates the ability of the visual system to resolve detail in high contrast. Binocular VA was measured with the POLA VistaVision Visual Chart System (DMD Med Tech srl. Torino, Italy), at a testing distance of 5.5 m (LogMAR scale). The same device was used to measure binocular contrast sensitivity to assess individuals' ability to distinguish between an object and the background, not based on size alone. Contrast sensitivity was measured at 6 spatial frequencies: 0.75, 1.5, 3, 6, 12, and 18 cycles per degree (cpd) at the recommended distance of 2.5 m, with the results expressed as decimals. This test employs Garbor patch gratings with three possible orientations: left, vertical, or right; the participants were asked to indicate the orientation, starting with the lowest spatial frequency and the highest contrast value.

Driving performance: driver self-regulation

Driving simulator

A fixed-based driving simulator with SIMAX DRIVING SIMULATOR v4.0.8 BETA software (SimaxVirt S.L., Pamplona, Spain) was used, as described in previous studies (Casares-

López et al., 2020; Ortiz-Peregrina, Ortiz, Casares-López, et al., 2020; Ortiz-Peregrina, Ortiz, Salas, et al., 2020; Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020; Ortiz et al., 2018). Participants underwent two training sessions (one week apart) with the driving simulator to familiarize them with the system. The training sessions lasted about 15 minutes and were conducted using similar routes to those used in experimental sessions, but without any traffic or pedestrians. If any symptoms of simulator sickness were noted, the session was interrupted, and the individual was excluded from the study.

In experimental drives, participants were asked to drive as they normally would, without imposing any requirement with regard to speed limit or signals obedience. The route was 12.5 km long and was divided into three different driving sections: dual carriageway, mountain road, and city, as shown in Figure 2.

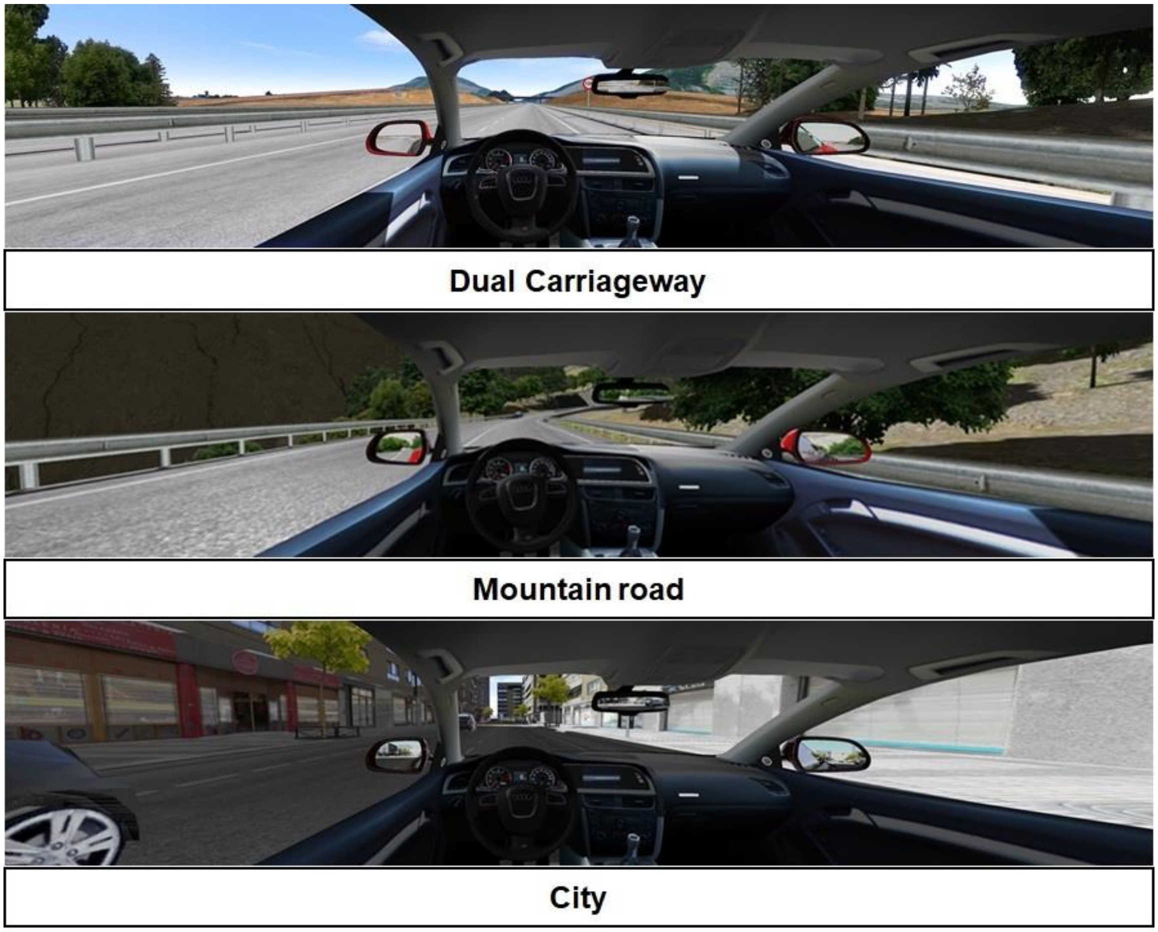

Figure 2. Screenshots of the different driving scenario sections included along the 12.5 km long driving simulation route.

We selected 10 different driving scenarios from these sections for analysis, each with certain characteristics regarding the road geometry and traffic complexity. Each driving scenario (road environment) was presented identically in both experimental conditions (baseline and after smoking cannabis). However, traffic cars could appear at different positions but with the same traffic flow (level of service). A description of the road scenarios used in the simulation is shown in Figure 3. The least complex scenarios were those driven on the dual carriageway (1 and 2). Despite having higher speed limits, this part of the route consists of two lanes in the same direction, moderate traffic and only gentle bends. On the mountain road, there was only one lane in each direction, with moderate oncoming traffic. Therefore, scenarios with a straight layout (3 and 5) and scenarios with slope (7 and 8) were of moderate complexity, and scenarios with sharp bends were complex (4 and 6). In the city, there was more visual clutter (signals, traffic lights, pedestrians, billboards, etc.), and the presence of other cars (those circulating and those parked around) making scenario 9 moderately complex and scenario 10 complex. We selected a representative length of 100 m on each scenario for data analysis. Thus, we ensured that the characteristics selected for a particular scenario were homogeneous and were not affected by the transition between scenarios. Drivers need some time to adapt their behavior between scenarios. This strategy has also been employed in previous studies about driver distraction (Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020; Oviedo-Trespalacios et al., 2017a).

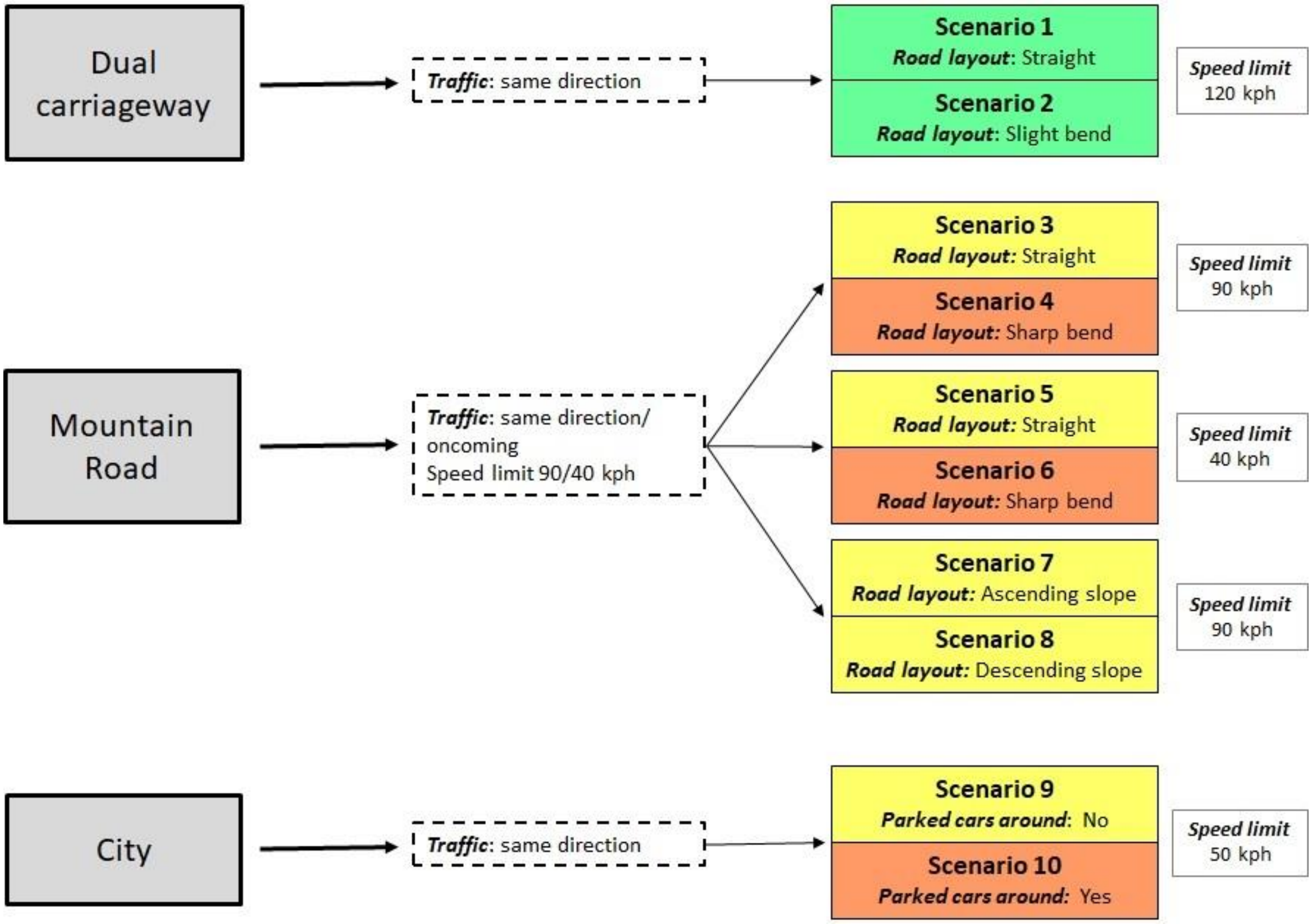

Figure 3. Description of the different road and traffic complexity scenarios selected for data analysis in this study. The degree of complexity is indicated by a color code (green = low, yellow = moderate, orange = high).

Driving performance analysis

Two different driving variables were selected for analysis. The speed adaptation (kph) referred to longitudinal control (i.e. the deviation from the speed limit [SL], calculated as the mean speed minus the SL), while the SDLP (m) variable (i.e. the standard deviation of the vehicle's center position with respect to the center of the lane) indicated the lateral control accuracy of the driver. The simulator registered the driving variables every 0.10 s and they were averaged for each scenario.

Statistical analysis

Statistical analyses were performed using the software SPSS 26.0 (SPSS Inc., Chicago, IL). Differences between the sessions (baseline vs. after smoking cannabis) in terms of the visual function variables and driver self-regulation parameters were assessed using paired *t*-tests. The driver self-regulation parameters were divided into two categories: longitudinal control (speed adaptation) and lateral control (SDLP). Then, the influence of cannabis consumption, road and traffic complexity (scenarios), and driver characteristics upon these two metrics was analyzed using two different generalized linear mixed models (GLMMs) with repeated measures (road scenarios during baseline and after smoking cannabis). The condition (baseline and after smoking cannabis), road scenario/complexity (10 levels), and participant age and gender were included as factors, and driver age, visual function (VA and contrast sensitivity), monthly cannabis use frequency, and driving experience were used as covariates. This model has been previously used to approximate driver performance (Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020; Oviedo-Trespalacios et al., 2017a) and accounts for correlations resulting from multiple observations in the same driver.

RESULTS

Effects on visual function

As shown in Figure 4, after smoking cannabis, the participants showed poorer visual test results, with the paired *t*-tests indicating a significant deterioration in VA ($t = -6.103$; $df = 30$; $p <$

0.001; 95% CI [−0.07, −0.03]) and contrast sensitivity (t = 4.439; df = 30; p < 0.001; 95% CI [6.98, 18.88]) for binocular viewing conditions.

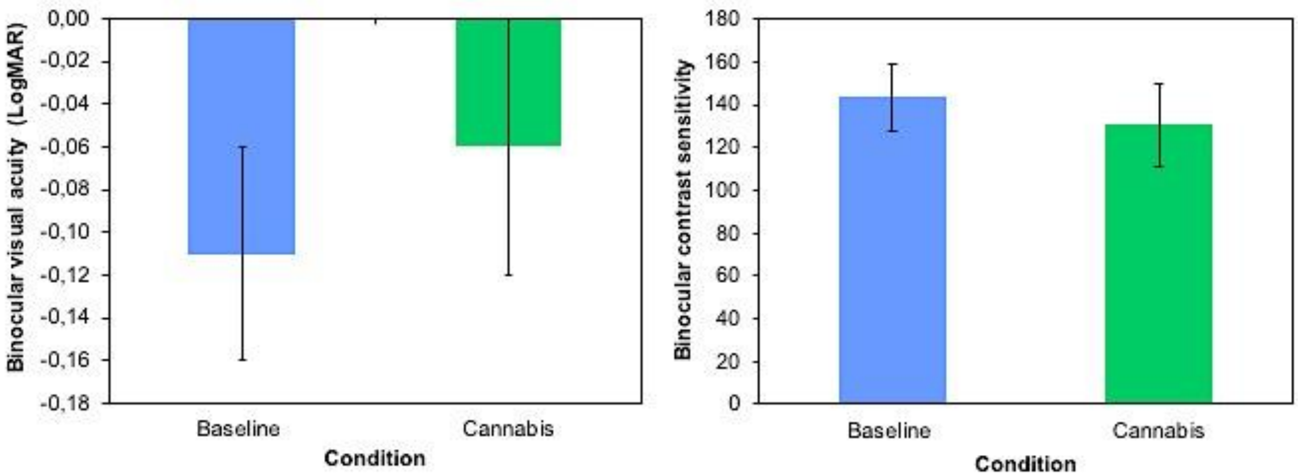

Figure 4. Visual test results for the baseline session and after smoking cannabis. Error bars represent the standard deviation (SD).

Driving performance in different scenarios: driver self-regulation of longitudinal and lateral control

Smoking cannabis did not result in significant changes in speed adaptation compared to the baseline session (Table 2). The participants drove under the SL in the dual carriageway scenarios at similar speeds for both conditions. On the mountain road, the participants generally adopted speeds below the limit for scenarios with a SL of 90 kph (scenarios 3, 4, 7, and 8), except for the baseline session in scenario 8 (a straight, descending slope, with a 90 kph SL) for which the mean speed adaptation was 1.62 ± 10.75 kph. Indeed, the mountain road scenario produced the biggest difference in speed adaptation between conditions. Considering the same section, drivers adopted speeds above the limit in the straight segment with a SL of 40 kph (scenario 5), but reduced their speed below the limit through the sharp bend with a 40 kph limit (scenario 6). In general, the speeds were lower when DUIC.

Cannabis consumption did not significantly affect lateral control in the scenarios analyzed (Table 2). SDLPs were higher in participants DUIC in the dual carriageway scenarios (1 and 2). Lateral control was similar on the straight segment and sharp bend with a 90 kph SL on the mountain road (scenarios 3 and 4) in both conditions, but was slightly worse in the baseline session. The opposite was true for scenarios 5 and 6; while in the straight segment with a 40 kph SL (scenario 5) SDLP increased when DUIC, SDLP was significantly lower along the curved segment with a 40 kph SL (scenario 6) after smoking cannabis. We found no difference in the SDLP in either session in scenarios involving a slope (scenarios 7 and 8), although lane control was poorer for the ascending slope compared to the descending one, with a mean SDLP approximately double that of the ascending the mountain road scenario. Finally, there were no differences in lane control in the city, regardless of the presence or absence of parked cars. Nevertheless, the differences between the conditions were higher in segments with parked cars.

TABLE 2. Comparisons of longitudinal control (speed adaptation) and the standard deviation of the lateral position (SDLP) in different road scenarios between conditions (baseline and after smoking cannabis).

	Longitudinal control: speed adaptation					**Lateral control: SDLP**				
Road scenario	Baseline (kph)	Cannabis (kph)	*t*	*df*	*p*-value	Baseline (m)	Cannabis (m)	*t*	*df*	*p*-value
Scenario 1: Dual carriageway, straight, 120 kph SL	-2.71 ± 7.77	-2.21 ± 14.17	-0.214	30	0.832	0.15 ± 0.10	0.22 ± 0.25	-1.523	30	0.138
Scenario 2: Dual carriageway, slight bend, 120 kph SL	-11.23 ± 11.38	-10.18 ± 14.64	-0.350	30	0.729	0.23 ± 0.20	0.39 ± 0.37	-2.195	30	0.036
Scenario 3: Mountain, straight, 90 kph SL	-29.50 ± 7.30	-28.45 ± 10.97	-0.459	30	0.649	0.45 ± 0.25	0.43 ± 0.19	0.349	30	0.730
Scenario 4: Mountain, sharp bend, 90 kph SL	-26.25 ± 11.78	-25.36 ± 9.73	-0.450	30	0.656	0.50 ± 0.31	0.42 ± 0.18	1.515	30	0.140
Scenario 5: Mountain, straight, 40 kph SL	4.16 ± 11.31	1.76 ± 10.52	0.844	30	0.405	0.16 ± 0.10	0.26 ± 0.29	-2.224	30	0.034
Scenario 6: Mountain, sharp bend, 40 kph SL	-1.01 ± 4.65	-2.01 ± 7.15	0.680	30	0.501	0.84 ± 0.24	0.68 ± 0.27	3.960	30	<0.001*
Scenario 7: Mountain, straight, ascending, 90 kph SL	-18.13 ± 6.19	-15.96 ±11.36	-0.960	30	0.345	0.40 ± 0.18	0.38 ± 0.23	0.628	30	0.535
Scenario 8: Mountain, straight, descending, 90 kph SL	1.62 ± 10.75	-1.77 ± 11.85	1.158	30	0.256	0.18 ± 0.08	0.23 ± 0.16	-1.274	30	0.213
Scenario 9: City, straight, parked cars, 50 kph SL	-16.07 ± 9.37	-18.61 ± 8.84	0.971	30	0.340	0.36 ± 0.24	0.48 ± 0.38	-1.013	30	0.319
Scenario 10: City, straight, no parked cars, 50 kph SL	-9.50 ± 8.44	-6.49 ± 9.65	-1.171	30	0.251	0.42 ± 0.40	0.44 ±0.40	-0.188	30	0.852

*Significant differences in speed adaptation and SDLP between the baseline session and cannabis session after Bonferroni correction for multiple comparisons (p<0.0025); SL: speed limit.

The influence of cannabis, road complexity, and personal traits on driving performance: predictors of longitudinal control

As shown in Table 3, the condition (not DUIC or DUIC) was not a significant predictor of speed adaptation in the GLMM. However, the road scenario or traffic complexity did significantly predict the speed selection in all the scenarios except scenario 2 (dual carriageway, slight bend, with a 120 kph SL) when compared to the reference category (a straight segment of the city, without parked cars, with a SL of 50 kph). Scenarios 3 and 4, both on the mountain road at a SL of 90 kph, involved the largest deviation below the SL with respect to the reference category. Contrary to our expectations, the participants drove faster on the segment with a sharp bend compared to the straight segment. In scenarios 5 and 6, with a SL of 40 kph, the participants drove above the SL, indicating that they felt safer driving faster along these segments. However, driving on a slope with a SL of 90 kph (scenarios 7 and 8), the participants drove an estimated speed of 8.68 kph below the SL while ascending and an estimated 9.15 kph above the limit while descending. Finally, the presence of parked cars in the city (scenario 8), caused the participants to drive significantly slower compared to the reference category (a straight city segment without parked cars).

The GLMM also indicated that, apart from the road and traffic complexity, driver characteristics including gender and visual status also significantly predicted speed adaptation. Thus, male participants showed estimated speeds 2.88 kph faster than their female counterparts. Similarly, binocular contrast sensitivity significantly influenced the speed, with an estimated increase in speed of 12.72 kph for every unit increase (better score) in this visual function.

TABLE 3. Generalized linear mixed model (GLMM) estimates of speed adaptation.

	Coefficient	*SE*	*t*-statistic	*p*-value	95% CI
Condition					
Baseline	----º	--º	----º	----º	----º
Cannabis	ns.	ns.	ns.	ns.	ns.
Road Scenario/complexity					
Scenario 1: Dual carriageway, straight, SL 120 kph	6.43	1.54	4.184	<0.001	[3.38, 9.48]
Scenario 2: Dual carriageway, slight bend, SL 120 kph	ns.	ns.	ns.	ns.	ns.
Scenario 3: Mountain, straight, SL 90 kph	-20.19	1.41	-14.325	<0.001	[-22.98, -17.40]
Scenario 4: Mountain, sharp bend, SL 90 kph	-16.55	1.59	-10.418	<0.001	[-19.69, -13.40]
Scenario 5: Mountain, straight, SL 40 kph	12.01	1.70	7.045	<0.001	[8.63, 15.39]
Scenario 6: Mountain, sharp bend, SL 40 kph	7.69	1.16	6.588	<0.001	[5.38, 9.99]
Scenario 7: Mountain, straight, ascending, SL 90 kph	-8.68	1.36	-6.393	<0.001	[-11.37, -5.99]
Scenario 8: Mountain, straight, descending, SL 90 kph	9.15	1.67	5.471	<0.001	[5.84, 12.47]
Scenario 9: City, straight, with parked cars, SL 50 km/h	-8.34	1.45	-5.755	<0.001	[-11.20, -5.47]
Scenario 10: City, straight, without parked cars, SL 50 kph	----º	----º	----º	----º	----º
Driver characteristics					
Age	ns.	ns.	ns.	ns.	ns.
Gender					
Male	2.88	0.73	3.924	<0.001	[1.44, 4.32]
Female	----º	----º	----º	----º	----º
Visual function					
Visual acuity	ns.	ns.	ns.	ns.	ns.
Contrast sensitivity	12.72	5.84	2.179	0.030	[1.25, 24.20]
Intercept	-38.13	12.48	-3.056	0.002	[-62.65, -13.61]
Number of observations	620				
AIC	4520.81				
BIC	4608.94				

----º Reference category; ns: not significant; SL: speed limit; AIC: Akaike's Information Criterion; BIC: Schwarz's Bayesian Criterion.

The influence of cannabis, road complexity, and personal traits on driving performance: predictors of lateral control

Table 4 shows the results of the GLMM estimates for the SDLP showing that the road characteristics and traffic complexity, but not the condition (not DUIC or DUIC), significantly predicted the SDLP. There was significantly lower SDLP for both scenarios on the dual carriageway compared to the reference category (scenario 10: city, straight, without parked cars). On the mountain road, the scenarios with a SL of 40 kph (scenarios 5 and 6) determined significant adaptations of lateral control; the SDLP was an estimated 0.25 units lower than the reference category in the straight segment (scenario 5) and 0.36 units higher when there was a sharp bend (scenario 6). For the scenarios involving a slope, only scenario 8 (mountain, straight, with a descending slope) significantly predicted SDLP, which was an estimated 0.22 units lower than the reference category.

Regarding the driver, some personal traits could significantly predict the SDLP. Age was associated with a 0.004-unit reduction for every extra year, and visual function was also a significant predictor, but only for contrast sensitivity. Thus, for every extra unit in contrast sensitivity (better score), our estimates indicated a SDLP reduction of 0.30 units, thereby representing a notable improvement in lateral control.

TABLE 4. Generalized linear mixed model (GLMM) estimates for SDLP.

	Coefficient	SE	t-statistic	p-value	95% CI
Condition					
Baseline	----º	----º	----º	----º	----º
Cannabis	ns.	ns.	ns.	ns.	ns.
Road Scenario/ complexity					
Scenario 1: Dual carriageway, straight, SL 120 kph	-0.26	0.02	-12.053	<0.001	[-0.30, -0.21]
Scenario 2: Dual carriageway, slight bend, SL 120 kph	-0.15	0.03	-4.331	<0.001	[-0.22, -0.08]
Scenario 3: Mountain, straight, SL 90 kph	ns.	ns.	ns.	ns.	ns.
Scenario 4: Mountain, sharp bend, SL 90 kph	ns.	ns.	ns.	ns.	ns.
Scenario 5: Mountain, straight, SL 40 kph	-0.25	0.02	-11.333	<0.001	[-0.29, -0.20]
Scenario 6: Mountain, sharp bend, SL 40 kph	0.36	0.04	9.852	<0.001	[0.28, 0.43]
Scenario 7: Mountain, straight, ascending, SL 90 kph	ns.	ns.	ns.	ns.	ns.
Scenario 8: Mountain, straight, descending, SL 90 kph	-0.22	0.02	-11.925	<0.001	[-0.26, -0.18]
Scenario 9: City, straight, with parked cars, SL 50 km/h	ns.	ns.	ns.	ns.	ns.
Scenario 10: City, straight, without parked cars, SL 50 kph	----º	----º	----º	----º	----º
Driver characteristics					
Age	-0.004	0.001	-2.758	0.006	[-0.007, -0.001]
Gender					
Male	ns.	ns.	ns.	ns.	ns.
Female	----º	----º	----º	----º	----º
Visual function					
Visual acuity	ns.	ns.	ns.	ns.	ns.
Contrast sensitivity	-0.30	0.12	-2.471	0.014	[-0.55, -0.06]
Intercept	1.16	0.27	4.288	<0.001	[0.63, 1.69]
Number of observations	620				
AIC	-35.71				
BIC	52.53				

----º Reference category; ns: not significant; SL: speed limit; AIC: Akaike's Information Criterion; BIC: Schwarz's Bayesian Criterion.

DISCUSSION

Cannabis consumption significantly altered visual functioning, as demonstrated by the tests for VA and contrast sensitivity employed in this study. Although early research was largely inconclusive about changes in VA after cannabis use (Adams et al., 1975), more recent work suggests that VA is significantly altered after smoking cannabis (Ortiz-Peregrina, Ortiz, Castro-Torres, et al., 2020). Furthermore, there is growing evidence to suggest that acute intoxication negatively affects contrast sensitivity (Ortiz-Peregrina et al., 2021), resulting in permanent impairments in cannabis users, especially at low spatial frequencies (Lalanne et al., 2017; Mikulskaya & Martin, 2018).

Cannabis use triggers negative cognitive and physical consequences, which may suggest that these drivers are aware of these declines, consequently causing them to adopt certain compensatory strategies to reduce the risk of crashing. However, the results we obtained in this study did not show this tendency. We found no statistically significant differences in speed adaptation between the baseline and cannabis sessions, and the GLMM did not highlight cannabis consumption as a significant predictor of speed adaptation. Other authors have found speed reductions when DUIC in driving simulator-based studies. In fact, Hartman et al., (2016) showed that drivers affected by cannabis adopted lower speeds and tended to drive below the SL. Brands et al., (2019) showed the same result, with their participants reducing their average speed by 0.9 kph 30 min after the administration of a low THC dose, and by 4.8 kph 30 min after receiving a high THC dose. Lenné et al., (2010) also reported a significant reduction in speed among participants in their high dose condition (two cannabis cigarettes containing 19 mg of THC).

In work more aligned with our findings, Downey et al., (2013) reported that fewer cannabis users under the influence of a high THC dose (a cigarette containing 3% THC) drove too fast compared to those in the low THC dose condition (a cigarette containing 1.8% THC). These findings indicate that speed selection may depend on the dose, which may explain the different result we found in our study. Our participants used cannabis in the same way as they did for their recreational consumption. However, this level of intake may mean that their doses were insufficient to generate an awareness of the impairment of their driving. Likewise, the type and strength of the cannabis they consumed could also have affected our results. Additionally, some of the studies mentioned above also included occasional cannabis users (Brands et al., 2019; Hartman et al., 2016).

According to the GLMM in our work, traffic and road complexity were significant factors contributing speed adaptation. Moreover, most of the features in the scenarios we studied also resulted in significant speed adaptations with respect to the reference category (i.e., scenario 10, city, without parked cars, 50 kph SL). The greatest speed self-regulation was observed in scenarios 3 and 4, both on the mountain road with a 90 kph SL. This indicates that drivers felt this section of the route was too complex for driving near the SL. In agreement with previous studies (Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020; Oviedo-Trespalacios et al., 2017a), curved roads usually caused the participants to drive more slowly than straight roads. Surprisingly, the drivers in our work adopted lower speeds in scenario 3 (straight) than in scenario 4 (sharp bend), in contrast to the results found for other pairs of scenarios in which the curved layout caused the participants to drive more slowly (scenarios 1 vs. 2 and scenarios 5 vs. 6). The reason for the apparently anomalous result obtained for scenarios 3 and 4 might have been because the straight segment was placed between two bends, thus perhaps influencing their overall chosen speed.

The speed selection also appeared to be significantly influenced by the slope on the mountain road. Our estimates indicated that the ascending slope was associated with slower speeds compared to the reference category (−8.68 kph), while the descending slope resulted in increased speed (+9.15 kph). Interestingly, this result is consistent with a previous study in distracted drivers (Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020). Furthermore, the result regarding driving in the city indicated that the presence of parked cars resulted in a reduction of the driving speed (scenario 9) with respect to the same section of the route without parked cars (scenario 10). In urban scenarios, participants drove under the SL for both conditions, indicating their awareness of the risk. These types of scenarios are generally considered more demanding because of the presence of visual clutter (Ho et al., 2001; Horberry et al., 2006; Michaels et al., 2017). Moreover, urban roads are surrounded by crucial and non-essential visual information (traffic signs, traffic lights, and a higher volume of pedestrians, parked cars, road marks, roundabouts, advertising billboards, buildings, etc.), all of which can detrimentally affect drivers' patterns of visual attention (Edquist et al., 2011).

Driver characteristics including gender and visual function could also significantly predict speed adaptation. In our work, male drivers selected higher speeds than females (2.88 kph faster) which is consistent with previous research showing that males tend to take more risks and commit more speeding violations (Factor, 2018; Oscar Oviedo-Trespalacios & Scott-Parker, 2017; Rhodes & Pivik, 2011; Varet et al., 2018). Similar patterns have also been identified in the case of distracted driving (Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020; Oviedo-Trespalacios et al., 2017a) and DUIC has been shown to be a more common behavior among males compared to females (Lloyd et al., 2020), with the latter showing an average cannabis consumption 2.3 times higher than for females in 2019 in Spain (EDADES, 2020).

Visual function (specifically contrast sensitivity), which has been found to be significantly altered by cannabis use, in accordance with previous studies (Lalanne et al., 2017; Mikulskaya & Martin, 2018; Ortiz-Peregrina et al., 2021), also significantly predicted speed adaptation in our work. This result suggests that the visual impairment that these drivers suffered after cannabis use determined speed adaptations. Within the driving environment there are stimuli of different contrast, spatial frequencies and illumination levels so that a good contrast sensitivity is crucial to integrate all the visual information and recognize signals, hazards or pedestrians during this task (Wood, 2002; Joanne Wood & Carberry, 2006). In agreement with our result, previous research also indicates that contrast sensitivity is important for driving and that this visual test can predict individuals' ability to drive more accurately than the standard VA test (Owsley & Mcgwin, 2010; Wood, 2002). Thus, the study by Owsley et al., (2001) on older drivers with or without cataracts demonstrated that participants who had been involved in a crash in the 5 years prior were 6–8 times more likely to have impaired contrast sensitivity in one or both eyes. In the same sample, accident risk were reduced after cataract surgery by 50% (Owsley et al., 2002). A recent study also demonstrated that, between several visual parameters, the deterioration in contrast sensitivity after smoking cannabis was the only visual test significantly associated with self-perceived visual impairment after cannabis use (Ortiz-Peregrina et al., 2021). This would explain our result that drivers under the influence of cannabis self-regulate their driving behavior based on contrast sensitivity and not on VA. This result is in agreement with other simulator-based studies in visually impaired drivers suffering cataracts or age-related macular degeneration, which demonstrated an association between poorer CS and lower speeds (Ortiz-Peregrina, Ortiz, Salas, et al., 2020; Szlyk et al., 1995).

According to the GLMM, cannabis consumption did not increase SDLPs, suggesting that our participants did not modify their lateral control when DUIC compared to the baseline. Independent comparisons for every scenario indicated that the SDLP was higher in scenarios 2 (dual carriageway, slight bend, with a 120 kph SL) and 5 (mountain road, straight segment, and a 40 kph SL), although scenario 6 showed a significantly higher SDLP in the baseline session. This may be because of an increased awareness of risk when driving on the curved road, as indicated by them adopting speeds well under the imposed limit (Onate-Vega et al., 2020; Oviedo-Trespalacios et al., 2018). According to the literature, the SDLP is one of the variables most sensitive to the effect of cannabis use in terms of driving ability, and it constitutes a valid measure for quantifying the degree of impairment (Ramaekers, 2018; Verster & Roth, 2014). After cannabis administration, other authors found significant increases in SDLP both in actual (Ramaekers et al., 2000) and simulated driving (Hartman et al., 2015).

Cannabis use has also been shown to have a dose dependent effect on SDLP. In a driving simulator, Veldstra et al., (2015) found a significant increase in SDLP in participants who had ingested a high dose (20 mg) of dronabinol, which they did not detect among participants who had taken a low dose (10 mg). However, our result is consistent with the findings of a recent study showing that inhalation of a 100 mg dose of cannabis by recreational cannabis users did not affect their ability to adhere to their lane while driving (Ogourtsova et al., 2018). The differences in these results might be because of the different doses administered to participants (Alvarez et al., 2021), as well as the timing of the driving task after cannabis use. As indicated above, in our study we considered recreational cannabis use, and so the individual doses selected by our participants may have influenced the results we obtained.

Some aspects of road and traffic complexity could also significantly predict the SDLP. Scenarios with estimated SDLPs lower than the reference category had a straight layout (scenarios 1 and 5) or only slight bends (scenario 2). However, scenario 6 (with sharp bends) generated an estimated SDLP that was 0.36 m higher than that of the reference category. Comparisons between road scenarios also showed that curved roads tended to generate higher SDLPs. Thus, the route characteristics also influenced the outcomes and layouts with bends usually generating higher SDLPs (Downey et al., 2013; Oviedo-Trespalacios et al., 2020; Papafotiou et al., 2005). Regarding the slope, scenario 8 (mountain, descending, with a 90 kph SL) produced an estimated SDLP lower than the reference category, perhaps because the slope resulted in more consistent control of the steering wheel because the driver had a more favorable perception of safety.

Some driver characteristics, especially age, also significantly predicted SDLP. In our study, the older the driver, the lower the SDLP, while previous research has found the opposite, with older drivers tending to deviate from their lane more (Ortiz-Peregrina, Ortiz, Casares-López, et al., 2020; Ortiz et al., 2018). In our work, with a sample comprising younger drivers, the participants closer in age to the sample lower limit were more likely to overcorrect the vehicle's position (higher SDLPs). This result might reflect the effect of driving experience rather than age, or could be the combined effect of both age and experience. More experienced drivers are more likely to be better prepared to cope with an impaired ability to drive, making them feel more confident when DUIC. In addition, older participants may have been less vulnerable to the effects of the drug as the result of more years of use. Visual function also significantly predicted SDLP, in this case, with better contrast sensitivity being correlated to a more stable lane position. Again, this result also agrees with previous work highlighting the importance of this visual parameter for driving ability (Owsley et al., 2001; Owsley & Mcgwin, 2010; Wood, 2002) and its relationship with perceived visual capacity when under the effect of cannabis (Ortiz-Peregrina et al., 2021). It is important to remember that increased SDLP can be interpreted as an impairment, i.e., the driver losing control of the vehicle or overcorrecting for their difficulty in controlling the vehicle. Our results indicate that the impairment in contrast sensitivity caused by cannabis may generate that drivers under the influence to feel less safe, increasing the SDLP. The relationship between contrast sensitivity and lateral control has also been highlighted by other simulator-based studies in subjects with impaired vision due to ocular pathologies such as age-related macular degeneration, glaucoma or cataracts (Ortiz-Peregrina, Ortiz, Salas, et al., 2020; Szlyk et al., 2002; Szlyk et al., 1995). Thus, the ability to properly drive the car within a lane may rely on visual guidance abilities mediated by contrast sensitivity, the reduction of which affects the detection of visual cues on the road.

Finally, the limitations of this study must be considered when interpreting the results presented here. Firstly, the use of a driving simulator did not allow us to represent the visual environment of driving with total realism, although the fidelity of these devices have improved. Nonetheless, our driving scenario was performed in daylight and under good weather conditions, and so factors such as poor road conditions with different contrast levels, or lightning changes that can occur in a real environment were not considered. Despite this, the validity of driving simulators has been proven, even for drivers under the influence of cannabis, and so they constitute a safe alternative (Micallef et al., 2018; Ungewiss et al., 2018). Moreover, the simulator used in this study has been successfully used in other work (Ortiz-Peregrina, Ortiz, Casares-López, et al., 2020; Ortiz-Peregrina, Oviedo-Trespalacios, et al., 2020; Ortiz et al., 2018). The order of presentation of the different types of route and driving scenarios was the same in both experimental drives, and this question could influence the results in some way. Future research and replication are needed in light of potential leaning effects. Nonetheless, it is important to note that drivers commonly travel the same routes in their day-to-day driving. Therefore, this experiment has some level of external validity. Secondly, each participant consumed a cannabis cigarette made as they usually would as part of their normal consumption. Thus, we were unable to establish a relationship between dose and effect in this work, which could have caused some of the differences we noted in our results. As in other work, we attempted to investigate recreational cannabis use, and so we tried to make the conditions under which each participant was operating similar to those they might drive in during a normal day with cannabis consumption (Ortiz-Peregrina et al., 2021; Ortiz-Peregrina, Ortiz, Castro-Torres, et al., 2020). Future research with different methodologies with respect to the dose, administration routes, type of cannabis, or the time elapsed after administration should be conducted to further explore the self-regulation behaviors of drivers under the influence of cannabis.

CONCLUSIONS

A large proportion of individuals say that they sometimes drive after smoking cannabis. Despite the negative consequences that cannabis use may generate in cognitive or physical capacities required for driving (such as vision), our results showed that recreational cannabis use did not result in driver self-regulation once visual impairments were controlled for. Additionally, as theoretically expected, road traffic complexity was associated with changes in longitudinal and lateral vehicle control. Among the road features that determined self-regulation behaviors, curved roads, slopes, or the presence of parked cars particularly stood out. Driver characteristics were also significant predictors with males adopting faster mean driving speeds with respect to the limit.

Furthermore, older driver age was linked to better lateral control and lower SDLPs. Finally, contrast sensitivity was an important visual parameter for driving. Thus, when individuals had better visual test results (i.e. without having smoked cannabis), tended to adopt faster speeds and have better lateral position control. Therefore, the contrast sensitivity function may be a good indicator of visual status which could help determine how drivers self-regulate their driving in normal conditions and when DUIC.

Key points:

Cannabis is the illicit drug most often detected in drivers.

Visual function is significantly deteriorated after cannabis use.

Smoking cannabis did not cause drivers to self-regulate their behaviors.

Road traffic complexity modulates driver self-regulation.

Visual function impairment, age, and gender were related to driver self-regulation.

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