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# Gaze entropy measures detect alcohol-induced driver impairment

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ABSTRACT

Driving under the influence of alcohol is an ongoing cause of road traffic accidents. The biphasic nature of alcohol effects on subjective experience appears to contribute to the prevalence of drink-driving, as people perceive the declining phase of the BAC curve as recovery from intoxication and are more willing to drive despite significant impairments in objectively measured functions. The present study investigates whether alcohol-induced changes in gaze behaviour can be detected during engagement in a simulated driving task. In a repeated-measures and placebo-controlled design, this study examines the biphasic influence of moderate alcohol intake (0.6 g/kg) on measures of gaze behaviour and simulated driving performance. Twenty-two healthy young adults completed three driving sessions (baseline, ascending and descending) under two conditions (placebo, alcohol) while their eye movements were simultaneously recorded. The results revealed that gaze behaviour as measured by gaze transition entropy (GTE) and stationary gaze entropy (SGE) and driving performance measured by the standard deviation of lateral position (SDLP) of the vehicle, were significantly affected by alcohol across the ascending and descending sessions. The alcohol-induced reduction in GTE with an increase in SGE is discussed as alcohol's impact on top-down modulation of gaze resulting in more dispersed and erratic pattern of visual scanning. The observed changes in gaze behaviour also mediated the influence of alcohol upon driving performance. These results have significant implications for the development of driver monitoring systems that can detect alcohol-induced impairment.

## 1. Introduction

The detrimental influence of alcohol intoxication upon driving performance is well documented (Irwin et al., 2017; Jongen et al., 2018; Wiedemann et al., 2018). Legislative efforts to reduce alcohol-related traffic accidents through maximum blood alcohol concentration (BAC) limits show considerable variability across nations as they range from 0 – 0.15% (WHO, 2014). Such variability suggests that while the impact of alcohol on driving performance may be undisputed, there is an apparent lack of consensus regarding the BAC level that renders alcohol a public hazard on the road. Furthermore, the persisting prevalence of drink-driving in regions that have implemented sanctions to deter such behaviour (Dowling et al., 2011; Freeman et al., 2016; Xiao et al., 2017) is testimony to the limitations of deterrent strategies alone in eliminating alcohol-related traffic accidents and fatalities. In particular, the sensitivity of BAC measures to variance in absorption and elimination rate due to genetic factors, experience, food intake and time elapsed since ingestion (Zakhari, 2006) makes it difficult to determine a definitive BAC limit that is indicative of impairment across all drivers and situations. Such limitations highlight the need for additional countermeasures such as real-time monitoring of alcohol-induced driver impairment. Given the rapidly increasing sophistication of driver monitoring systems (DMS: Aghaei et al., 2016; Fitzharris et al., 2017; Lee et al., 2011), equipping such technology to detect alcohol-induced impairment may provide additional means for reducing alcohol-related traffic accidents by enabling drivers to self-monitor in real-time. Hence, identifying key biobehavioural processes that are both essential for driving and sensitive to alcohol effects may encourage the development of DMS with capabilities to detect alcohol-induced impairment.

Good visual function is a prerequisite for driving, as drivers rely on visual information to monitor and navigate their environment (Owsley and McGwin, 2010). By extension, gaze behaviour, the automatic and deliberate movement of the eyes to scan the environment, is a critical process that enables drivers to sample spatially distributed visual information (Land, 2006). Saccadic eye movements, the fast transition of the eyes from one fixation location to another, are susceptible to alcohol intoxication as it has been reported to affect their accuracy, amplitude and velocity profiles (Fransson et al., 2010; Schmitt et al.,

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2013; Vorstius et al., 2008). Moreover, alcohol impairs executive faculties such as visuospatial working memory (Saults et al., 2007; Schweizer et al., 2006) and attentional control (Colflesh and Wiley, 2013; Roberts et al., 2014); which are closely involved in the top-down or goal-driven predictive control of eye movements (Moore and Fallah, 2001; Parr and Friston, 2017; Van der Stigchel and Hollingworth, 2018). Such influence of alcohol on the initiation and execution of eye movements suggests that it may have a systemic effect on overall gaze behaviour, whereby the attenuation of top-down contribution to gaze control may lead to a less efficient visual scanning behaviour.

In a recent publication, we reported that alcohol intoxication significantly alters visual scanning behaviour across the ascending and descending phases of the BAC curve as indicated through gaze entropy measures (Shiferaw et al., 2019a). Gaze entropy refers to methods of assessing gaze behaviour through quantifying the spatial distribution (stationary gaze entropy: SGE) and transition pattern (gaze transition entropy: GTE) of eye movements (Krejtz et al., 2014). SGE measures the overall uncertainty or entropy in where a person looks during a given viewing period. GTE, on the other hand, measures the uncertainty associated with the next location of gaze, given current position of the eyes. In this case, the uncertainty measured refers to the transition pattern of eye movements, or the probability of transitioning from one specific region of fixation to the next. It is hypothesised that GTE provides an estimation for the level of top-down modulation in gaze control; and as such, there is a theoretical optimal GTE range for a given task, where the level of uncertainty is relative to the complexity of the visual environment and task requirements (Shiferaw et al., 2019b). An increase in GTE above the optimal range likely indicates top-down interference such as the case of anxiety (Allsop and Gray, 2014), while a reduction suggests reduced top-down modulation, which is likely the case with depressant agents like alcohol (Shiferaw et al., 2019a). Depending on the visual requirement of the task, such changes in GTE can lead to an increase or reduction in overall spatial dispersion of gaze as measured through SGE, reflecting a mismatch between task requirement and overall gaze allocation. For a more detailed discussion on the theoretical relationship between these measures, see Shiferaw et al. (2019b).

Gaze entropy measures have been employed to detect operator impairment in visually demanding tasks such flight control, performance of surgical procedures, and driving (Di Stasi et al., 2016; Diaz-Piedra et al., 2019; Schieber and Gilland, 2008; Shiferaw et al., 2018); and may therefore be suitable measures for detecting alcohol-induced impairment among drivers. Previous application of these measures to driving setting has examined the influence of age and distraction (Schieber and Gilland, 2008), and sleep-deprivation along with time-on-task effects (Shiferaw et al., 2018). These studies reported GTE to be lower in older than younger drivers when engaged in a secondary visual task; and that it increased following one night of total sleep deprivation. The increase in GTE among sleep-deprived drivers was also accompanied by a reduction in SGE, which predicted deterioration in driving performance. To date, no studies have examined how alcohol may alter drivers' gaze entropy metrics, and whether such influence is systematically associated with decrement in driving performance. In characterising the influence of alcohol on gaze behaviour as a potential means to detect impairment in real time, it is important to understand whether there are variations across the BAC curve as drivers are more likely and willing to drive during the descending phase (Amlung et al., 2014; Weafer and Fillmore, 2012).

The present study employs a simulated driving task to investigate how alcohol alters drivers' gaze entropy metrics during the ascending and descending phases of intoxication. As a depressant agent, we expect alcohol to reduce GTE, which was supported by findings from our previous investigation (Shiferaw et al., 2019a), along with a similar reduction in SGE. Unlike the highly controlled and limited presentation of visual information in our previous experiment, however, a driving environment contains vast and more complex visual information which the driver needs to systematically sample through structured gaze allocations to guide their action (Land and Lee, 1994). As such, alcohol-induced reduction in GTE may be accompanied by an increase in SGE, reflecting the disruption of structured visual scanning behaviour by intoxication as it reduces top-down regulation of action (Beaton et al., 2018).

## 2. Materials and methods

The present study used a repeated-measures design with a single-blind placebo and baseline control. The study protocol was approved by Swinburne University Human Research Ethics Committee (SUHREC) for meeting the national statement on ethical conduct in human research (NHMRC, 2015) prior to commencement of the study.

### 2.1. Participants

Participants were recruited through social media and flyer distribution at the Hawthorn campus of Swinburne University of Technology. To participate in this study, individuals had to be aged 18–40 years and have a valid Australian or international driver licence (including probationary licence but not learner permits). Further inclusion criteria were over all good health with no history of alcoholism, liver or kidney failure, not currently taking prescribed or recreational drugs, and not pregnant or lactating. For the purpose of eye tracking, participants had to have normal vision or corrected with contact lenses. The Alcohol Use Identification Test (AUDIT) was used to screen drinking habit, and all eligible participants had to have dependence score $< 4$ and total AUDIT score $\leq 20$ (Babor et al., 2001). Following screening, a total of 22 participants (11 female, 11 male) eligible participants were recruited. At the end of their last visit, participants were compensated for their time with $75 gift voucher.

### 2.2. Equipment set-up and driving task

This study utilised the UC win/Road driving simulator (Forum 8, Japan). The hardware set up consisted of a stationary vehicle base (driver seat and dashboard) with control (steering, brake, speed, gear and indicator) and surround audio-visual display – see Fig. 1. The visual display was presented on three 144 cm (width) by 81 cm (height) monitors with 1920 × 1080pixel resolution at 60 Hz refresh rate. The driver seat, which allowed adjustment to accommodate individual preference, was located approximately 180 cm from the middle monitor. Gaze behaviour was recorded using a cap-mounted monocular eye tracker by SensoMotoric Instruments (SMI, Germany) with a 50 Hz sampling rate. Prior to each driving session, BAC level was assessed through breath alcohol content (BrAC) reading using the Lion Alcometer SD-400 digital breathalyser (Lion Laboratories).

The task consisted of a 20-minute simulated drive on a highway road at a maximum speed of 100 km/h with minimal randomised traffic flow. Participants were instructed to keep to the left lane, and if they encounter a slow vehicle ahead to overtake as they would in real driving situation (i.e. indicate and check mirrors). To avoid anticipation associated with driving the same simulation across the three sessions in one visit, three simulations with similar traffic levels and scenery were used, and their order of use (either at baseline, ascending or descending) was randomised across participants. Each participant drove the same simulations in the same order across placebo and alcohol conditions. A different simulation was used for training sessions.

### 2.3. Procedure

Eligible participants were required to make three separate visits to the Centre for Human Psychopharmacology lab in Melbourne, Australia. During the first visit, participants completed the AUDIT form, provided informed consent and if their eligibility was confirmed, they


**Fig. 1.** Experimental set-up consisting of the driving simulator and eye tracking equipment fitted onto a participant.

completed a training session to be familiarised with the driving simulator. As some individuals can experience simulator sickness, a formal 20-minute driving session was conducted after initial training, following which the simulator sickness questionnaire was administered (Kennedy et al., 1993). Those who did not experience simulator sickness were booked for two more visits to perform the task under placebo and alcohol conditions in a randomised cross-over order. For their follow up visits, participants were instructed to abstain from alcohol for 24 h as well as avoiding caffeine for two hours, food for 2 -hs and nicotine for 1 -h prior to each appointment. They were also advised to have a light meal no earlier than 3 -hs and no later than 2 -hs before their appointment for each visit.

At the start of each follow-up visit, participants confirmed their adherence to the alcohol, food and nicotine intake restrictions. After being breathalysed, they sat in the driving simulator and were fitted with the eye tracking equipment to complete eye tracker calibration process prior to commencing the baseline drive. Following the baseline drive, they were given a beverage to consume within 10 min. For the alcohol condition, the beverage was vodka (40% alcohol, Absolut brand) measured according to each participant's body weight (0.6 g/kg) mixed with orange juice, while in the placebo condition the beverage consisted mostly of orange juice with only a negligible amount (3 ml) of vodka floated on top.

Upon finishing the beverage, participants rinsed their mouth with water to reduce the amount of alcohol that may be present in the mouth cavity and be detected during breath analysis. Periodic breath sampling (approximately every 5-minutes) commenced ten minutes after each participant finished drinking the beverage. In the alcohol condition, the ascending limb was determined by three increasing BrAC readings (e.g., if the third sample presented a lower reading than the second, another sample was taken after 5 min). Following the ascending testing session, participants were breathalysed then given 15 min break before breath sampling recommenced. Similar to the ascending session, the descending session was determined by three decreasing breath samples. This procedure was repeated in the placebo condition, but all three BrAC samples before each testing session were 0.00. Both ascending and descending drive sessions were conducted in the same way as baseline, following the same set-up and calibration process for eye tracking.

### 2.4. Subjective assessment

The Biphasic Alcohol Effects Scale (BAES) is a validated measure used to assess differential effects of alcohol on self-reported mood during the ascending and descending limbs (Earleywine and Erblich, 1996). The two subscales of BAES, stimulative and sedative, have been reported to increase during the ascending and descending limbs respectively (Morean and Corbin, 2010). A shorter version of this scale (B-BAES), which consists of 6 questions in total with response range of 0–10, has been validated as a reliable measure for detecting subjectively reported biphasic effects of alcohol (Rueger et al., 2009; Rueger and King, 2013). In the present study, the B-BAES was used to enable a more efficient process for taking measures at ascending and descending limbs.

### 2.5. Objective measures

Visual scanning behaviour was assessed through fixation rate, fixation duration, GTE and SGE measures. Fixation events were filtered using a built-in dispersion-based event detection algorithm (SensoMotoric Instruments, 2011), with a minimum duration of 80 ms and 100px maximum dispersion thresholds. Because the eye tracking used was monocular, gaze locations are represented by spatial values in pixels rather than visual angle. Spatial distribution of fixations was visually inspected, and valid area of interest defined as a 1000px (width) x 700px (height) space. Fixations that fell outside this area were discarded from further analysis.

For the purpose of entropy calculations, the valid area of interest (1000 × 700px) was divided into 280 state spaces of 50 × 50px, resulting in a maximum entropy of $\log_2(280) = 8.129$, which was used to normalise both SGE and GTE values as within state transitions were considered valid for GTE (Shiferaw et al., 2019b). The rationale for generating a grid of 280 state spaces was to approximate spatial specificity of fixations to the level of precision required by the task, which included judgment of lane position (Shiferaw et al., 2018). To calculate SGE, Shannon's entropy equation (Shannon, 1948) was applied as follows where, $x$ is a set of fixations generated during a driving session, $n$ is the number of state spaces occupied by fixations, $i$ indexes occupied state spaces, and $p_i$ represents the proportion of fixations within the $i^{th}$ state space:

$$SGE(x) = -\sum_{i=1}^{n} (p_i) log_2(p_i)$$

Similarly, GTE was calculated by applying the conditional entropy equation (Ciuperca and Bernard, 2005) to 1st order transition matrices of fixation sequences where $p_i$ represents the stationary distribution and $p(i|j)$ denotes the probability of transitioning from $i^{th}$ (prior state) to $j^{th}$ (current state) space:

$$GTE(x) = -\sum_{i=1}^{n} p_i \sum_{j=1}^{n} p(i|j) log_2 p(i|j)$$

Driving performance was assessed through standard deviation of

lateral position (SDLP). In simulated driving studies, SDLP is considered the most reliable and sensitive measure to detect alcohol-related performance impairment (Irwin et al., 2017). Deviation of the vehicle from the centre of the lane is recorded in centimetres with negative and positive numbers corresponding to left and right deviations respectively. Standard deviation of these values across the driving duration provides the SDLP variable, which reflects capacity to maintain lane position (Verster and Roth, 2011). To reduce the influence of intentional deviation from the lane centre, data points during lane change events were removed from SDLP calculation. Intentional lane change events were marked by the use of indicators, which the participants were instructed to perform, as well as visual inspection of lane position plots. Average speed was assessed for the whole drive duration.

## 3. Results

A total of 22 participants (11 female, 11 male) with a median age of 24 (range: 19–36) completed this study. The majority of participants (86%) stated their ethnicity as Caucasian, while 9% identified as Asian and 5% as Hispanic. Participants were mostly non-smokers, with only 3 indicating that they were social smokers and did not smoke on testing days. On average, participants held their current driver license for 6.6 years (SD = 5.13). As indicated by the mean total AUDIT score (Mean = 7.27, SD = 1.36), the participants were not heavy drinkers or at a high risk of alcohol dependence (Babor et al., 2001).

### 3.1. Breath alcohol concentration

The respective BrAC at the start of the ascending (Mean = 0.05, SD = 0.01) and descending (Mean = 0.04, SD = 0.01) test sessions occurred at 26.59 (SD = 5.76) and 84.02 (SD = 7.34) minutes after ingestion of alcohol. The highest BrAC (Mean = 0.06, SD = 0.01) was observed after completion of the ascending test session and prior to the start of the descending session. BrAC was higher during the ascending than the descending test session ($t[21] = 3.30$, $p = 0.003$, mean difference = 0.004, 95% CI: [0.002, 0.007]).

### 3.2. Subjective alcohol effects

A 2 (condition: alcohol, placebo) by 3 (session: baseline, ascending, descending) factorial ANOVA was conducted to assess subjective B-BAES scores. The stimulative score was affected by condition ($F[1,21] = 6.51$, $p = .019$, $\eta_p^2 = .24$), session ($F[2,42] = 3.61$, $p = .036$, $\eta_p^2 = .15$), and their interaction ($F[2,42] = 5.35$, $p = .009$, $\eta_p^2 = .20$). Post-hoc analysis with Holm-Bonferroni correction revealed that for the alcohol condition the stimulative score during the ascending limb was higher than baseline (mean difference: 2.18, 95% CI: 0.46–3.91, $p = .004$) and descending sessions (mean difference: 1.91, 95% CI: 0.18–3.63 $p = .02$). During the ascending session, the stimulative score was also significantly higher in the alcohol condition than placebo (mean difference: 2.91, 95% CI: 0.67–5.12 $p = .004$). The placebo condition did not vary across sessions (all $p > .10$).

The total sedative score was also affected by condition ($F[1,21] = 10.69$, $p = .004$, $\eta_p^2 = .34$), session ($F[2,42] = 9.42$, $p < .001$, $\eta_p^2 = .31$), and their interaction ($F[2,42] = 8.74$, $p < .001$, $\eta_p^2 = .29$). In the alcohol condition, the sedative score during the descending session was significantly higher than baseline (mean difference: 4.82, 95% CI: 2.53–7.10, $p < .001$) and ascending (mean difference: 2.73, 95% CI: 0.44–5.01, $p = .007$) sessions. The difference between baseline and ascending sessions of the alcohol condition did not reach significance ($p = .07$). The sedative score during the descending session was also higher in the alcohol condition than placebo (mean difference: 4.36, 95% CI: 1.81–6.92, $p < .001$). The placebo condition did not vary across sessions (all $p > .10$). A summary of the B-BAES scores is presented in Table 1.

**Table 1**
Summary of the B-BAES scores across test session and condition.

| B-BAES Subscale | Test Session | Placebo Mean (95% CI) | Alcohol Mean (95% CI) |
|---|---|---|---|
| Stimulative | baseline | 16.77 (13.88,19.67) | 17.00 (14.92,19.08) |
| Stimulative | ascending | 16.27 (13.76, 18.79) | 19.18 (17.14, 21.22) $^{B**}$ |
| Stimulative | descending | 15.86 (13.25, 18.48) | 17.27 (15.02, 19.52) $^{A*}$ |
| Sedative | baseline | 7.05 (4.44, 9.65) | 6.82 (5.20, 8.44) |
| Sedative | ascending | 6.95 (4.43, 9.48) | 8.91 (6.97, 10.85) |
| Sedative | descending | 7.27 (4.85, 9.69) | (9.97, 13.29) $^{B***; A**; P***}$ |

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ with Holm-Bonferroni correction for 9 tests.
B compared to baseline session of the alcohol condition.
A compared to ascending session of the alcohol condition.
P compared to placebo condition of the same session.

### 3.3. Condition by session effects on gaze behaviour

The same 2 (condition: alcohol, placebo) by 3 (session: baseline, ascending, descending) factorial ANOVA was conducted for all gaze variables which consisted of fixation rate, fixation duration, and normalised GTE and SGE. Due to technical failure, gaze data were not properly recorded for one participant during one driving session. As a result, analysis for ocular variables was conducted on data from the remaining 21 participants. Fixation rate was not altered by condition ($F[1,20] = 0.19$, $p = .67$, $\eta_p^2 = .01$), session ($F[2,40] = 0.21$, $p = .81$, $\eta_p^2 = .01$) or their interaction ($F[2,40] = 0.15$, $p = .33$, $\eta_p^2 = .05$). Similarly, fixation duration was not altered by condition ($F[1,20] = 0.20$, $p = .66$, $\eta_p^2 = .01$), session ($F[2,40] = 1.22$, $p = .31$, $\eta_p^2 = .06$), or their interaction ($F[2,40] = 0.52$, $p = .60$, $\eta_p^2 = .03$).

GTE was significantly altered by alcohol ($F[1,20] = 11.35$, $p = .003$, $\eta_p^2 = .36$), but not test session ($F[2,40] = 0.31$, $p = .73$, $\eta_p^2 = .02$), and the interaction term did not reach significance ($F[2,40] = 2.80$, $p = .07$, $\eta_p^2 = .12$). GTE was lower in the alcohol condition than placebo at both ascending (mean difference: 0.012, 95% CI: 0.0001 – 0.022, $p = .03$) and descending (mean difference: 0.016, 95% CI: 0.005 – 0.027, $p = .004$) sessions.

Alcohol also had a significant effect on SGE ($F[1,20] = 10.22$, $p = .005$, $\eta_p^2 = .34$), but not test session ($F[2,40] = 0.96$, $p = .39$, $\eta_p^2 = .05$), and the interaction term did not reach significance ($F[2,40] = 2.76$, $p = .08$, $\eta_p^2 = .12$). SGE was higher in the alcohol condition than placebo at both ascending (mean difference: 0.037, 95% CI: 0.003 – 0.071, $p = .03$) and descending (mean difference: 0.048, 95% CI: 0.014 – 0.082, $p = .004$) sessions.

As it was hypothesised that alcohol's attenuation of top-down modulation on gaze control would result in GTE reduction, which in turn may increase SGE, we also conducted mediation analysis to assess whether the impact of alcohol on SGE is mediated by its influence on GTE. For this purpose, analysis was only conducted on ascending and descending sessions. In the first linear model ($F[21,62] = 14.67$, $p < .001$, $R^2 = .78$), alcohol alone significantly increased SGE ($\beta = .31$, $p = .003$). The second model ($F[21,62] = 6.24$, $p < .001$, $R^2 = .57$) revealed that alcohol significantly reduced GTE ($\beta = -.35$, $p = .01$). Inclusion of GTE as a predictor of SGE improved the first model ($F[1,61] = 25.15$, $p < .001$, $\Delta R^2 = .06$), with reduction in GTE significantly predicting increase in SGE ($\beta = -.42$, $p = .001$) while the effect of alcohol declined ($\beta = .17$, $p = .08$). Causal mediation analysis with 1000 simulations indicated that the effect of alcohol on SGE increase is fully mediated by reduction in GTE as the indirect effect was significant ($\beta = .15$, 95% CI: [.01, .33], $p = .03$), but not the direct effect ($p = .16$). This mediation effect is graphically presented in Fig. 2D.

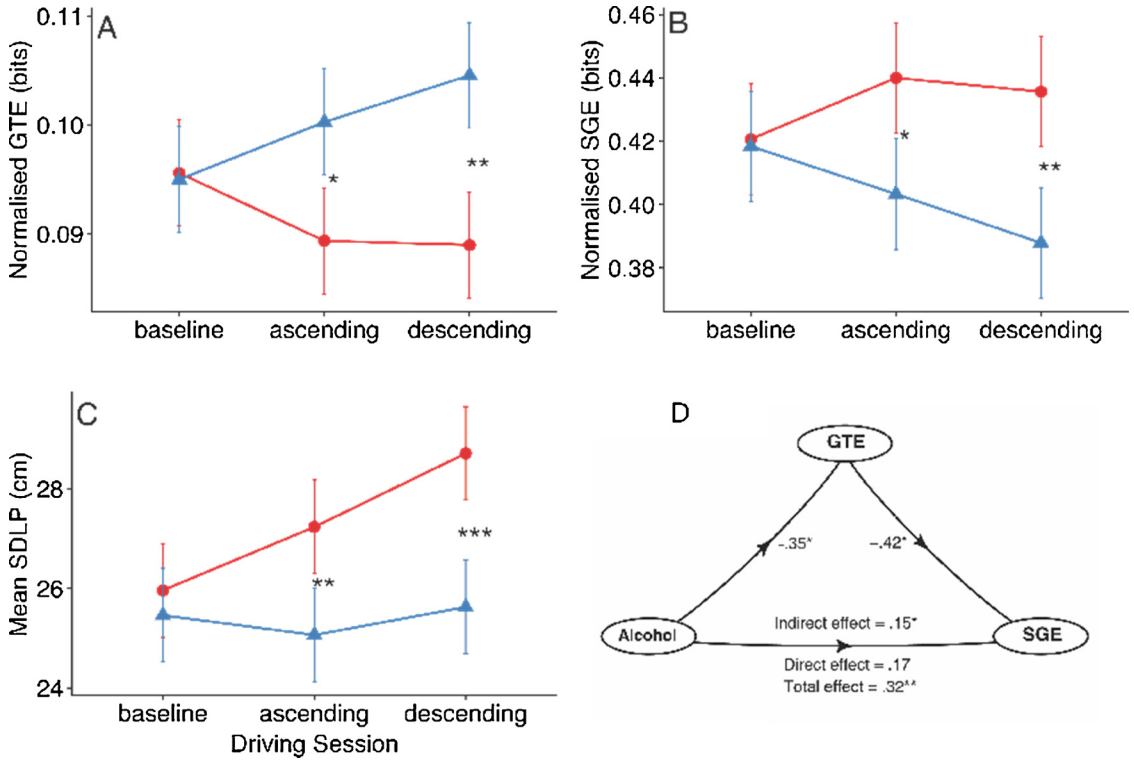


**Fig. 2.** Mean GTE (A), SGE (B), and SDLP (C) for alcohol (●) and placebo (▲) conditions across the driving sessions. Error bars indicate standard error of the mean. Panel D depicts the mediation plot indicating that the influence of alcohol on SGE is fully mediated by its reduction of GTE.
*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ with Holm-Bonferroni correction (panels A – C).

### 3.4. Condition by session effects on driving performance

SDLP was significantly affected by condition ($F[1,21] = 14.65$, $p < .001$, $\eta_p^2 = .41$), but the effect of driving session ($F[2,42] = 3.20$, $p = .051$, $\eta_p^2 = .13$) and the interaction term ($F[2,42] = 3.13$, $p = .054$ $\eta_p^2 = .13$) did not reach significance. Alcohol significantly increased SDLP at both ascending (mean difference: 2.17, 95% CI: 0.06–3.74, $p = .008$) and descending (mean difference: 3.08, 95% CI: 1.51–4.65, $p < .001$) sessions. Mean SDLP for each condition and across the driving sessions are presented in Fig. 2C.

### 3.5. Prediction of SDLP by gaze entropy measures

Similar to the mediation analysis in section 3.3, linear regression models were fitted to examine the effect of alcohol on SDLP across the ascending and descending sessions, as well as how GTE and SGE mediate this effect. In the base model, alcohol alone ($F[21,62] = 9.15$, $p < .001$, $R^2 = .67$) was an overall significant predictor of SDLP increase ($\beta = .55$, $p < .001$). In the second model ($F[21,62] = 6.24$, $p < .001$, $R^2 = .57$), alcohol was also observed to significantly predict reduction in GTE ($\beta = -.35$, $p = .01$). Including GTE as a predictor of SDLP improved the base model ($F[1,61] = 7.63$, $p = .01$, $\Delta R^2 = .04$), where reduction in GTE predicted increase in SDLP ($\beta = -.32$, $p = .01$) in addition to the positive effect of alcohol ($\beta = .44$, $p = .001$). Causal mediation analysis indicated that the effect of alcohol on SDLP increase is partially mediated by GTE as both the indirect ($\beta = .11$, 95% CI: [.02, .26], $p = .02$) and direct ($\beta = .44$, 95% CI: [.18, .69], $p = .002$) effects were significant. Overall, 20% of alcohol's influence on SDLP increase was mediated through its impact on GTE ($\beta = .20$, 95% CI: [.03, .48], $p = .02$).

The same steps were carried out to examine the degree to which alcohol effects on SDLP were mediated by associated changes in SGE. Alcohol ($F[21,62] = 14.67$, $p < .001$, $R^2 = .78$), increased SGE ($\beta = .31$, $p = .003$); and the inclusion of SGE as a predictor of SDLP improved the base model ($F[1,61] = 11.90$, $p = .001$, $\Delta R^2 = .05$), with alcohol ($\beta = .39$, $p = .003$) and the increase in SGE ($\beta = .50$, $p = .001$) significantly predicting SDLP increase. Mediation results indicated that the influence of alcohol on SDLP was also partially mediated by SGE as both indirect ($\beta = .16$, 95% CI: [.01, .36], $p = .03$) and direct ($\beta = .39$, 95% CI: [.05, .71], $p = .03$) effects were significant. The overall proportion of alcohol effect on SDLP mediated by SGE was 28% ($\beta = .28$, 95% CI: [.04, .78], $p = .03$). These mediation effects are depicted in Fig. 3.

## 4. Discussion

This study utilised gaze entropy measures to evaluate changes in visual scanning behaviour across the ascending and descending phases of moderate alcohol intoxication during a simulated driving task. Overall, alcohol altered gaze behaviour by reducing GTE and increasing SGE, but its impact on fixation rate and duration did not reach significance. This lack of significant effects on fixation parameters suggests that when participants are presented with a complex task or stimuli, alcohol may have greater influence on the overall distribution of gaze than specific characteristics of ocular events (Harvey et al., 2013; Harvey, 2014). The changes in GTE and SGE were also accompanied by a deterioration in driving performance as indicated by an increase in SDLP. Furthermore, the impact of alcohol on driving performance was partially mediated by its influence on gaze behaviour. Despite BrAC being significantly lower during the descending session than ascending, the effect of alcohol on gaze entropy measures and driving performance persisted across both sessions. Taken together, these results illustrate that alcohol reduces top-down regulation of gaze control which leads to a less structured visual scanning behaviour; thereby reducing visuospatial awareness of the driver and contributing to performance decrement.

The structure or predictability of gaze patterns during driving is related to learned visual scanning patterns that are specific to the task

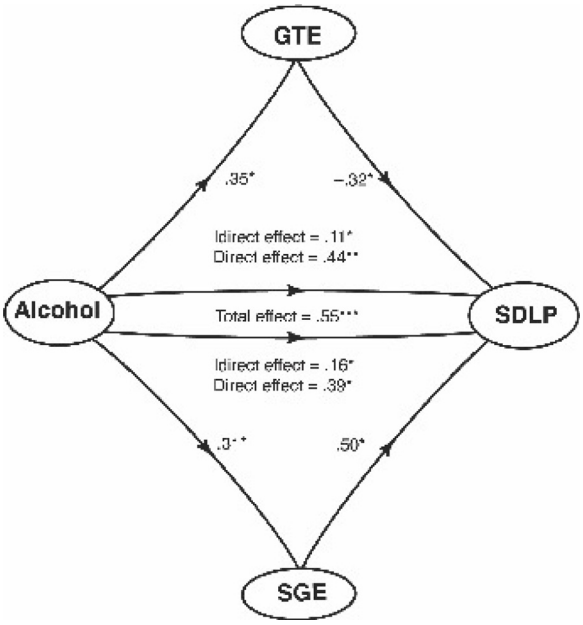


**Fig. 3.** Mediation plot indicating that the influence of alcohol on SDLP is partially mediated by its impact on GTE and SGE measures.
*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

(Land, 1992; Pradhan et al., 2009; Wann and Swapp, 2000). Such learned skill or prior knowledge is an aspect of top-down modulation on gaze control that serves to optimise sampling of relevant visual information for a given task (Chen and Zelinsky, 2006; Malcolm, 2010). Modulatory top-down mechanisms that control behaviour are particularly sensitive to alcohol intoxication (Beaton et al., 2018; Kovacevic et al., 2012; Marinkovic et al., 2012; Rosen et al., 2016). Given that GTE reflects the level of top-down input involved in gaze orientation (Shiferaw et al., 2019b), the reduction in GTE we observed may indicate alcohol-induced decline in the top-down modulation of gaze control. Together with the increase in SGE, these results suggest that alcohol leads to a more dispersed and random distribution of gaze due to its deleterious effects on top-down processes that modulate gaze control for task-relevant visual scanning, which is critical for driving.

The above interpretation is consistent with extant evidence in the literature that highlight the disruptive nature of alcohol upon oculomotor control. Such reports are predominantly based on measures of specific ocular events such as evoked nystagmus (Romano et al., 2017), saccade generation towards and away from a target (Roche and King, 2010), as well as measures of velocity, latency and accuracy (Roberts et al., 2014; Vorstius et al., 2012). While such ocular parameters provide useful information regarding the extent of cognitive disruption inflicted by alcohol intoxication (Zoethout et al., 2011), they require highly controlled settings and specifically designed tasks to measure; which makes them unsuitable for applied settings like driving. Hence, gaze entropy measures are advantageous in this regard as all that is required to generate them is the spatial coordinates of any given sequences of shifts in gaze location.

Subjectively, participants in the present study experienced greater stimulation and sedation during the ascending and descending sessions respectively, suggesting the presence of a biphasic effect. It is well established that alcohol has biphasic influence on subjective experience while its impact on objectively measured cognitive functions and driving performance remain through to the descending phase (Addicott et al., 2007; Holland and Ferner, 2017). Numerous studies have also reported that the reduction in stimulation and subjective estimation of intoxication level during the descending phase contributes to more individuals' willingness to drive (Amlung et al., 2014; Starkey and Charlton, 2014). Thus, it is critical that potential measures to be incorporated into driver monitoring systems for the purpose of detecting alcohol-induced impairment are sensitive to its effect across the BAC curve, and particularly the descending phase. The results from the present study illustrate that alcohol-induced deterioration of visual scanning behaviour, which persists across the BAC curve, can be detected through gaze entropy measures.

To our knowledge, this publication is the first to present detection of alcohol-related driver impairment through gaze entropy measures. Based on these findings and our previous report (Shiferaw et al., 2019a), it appears that alcohol reduces GTE but the direction of its impact on SGE may be dependent on the task and visual environment. The implication of such differential changes in SGE within the context of driving is that the impact of alcohol on the spatial dispersion of gaze may vary depending on the traffic environment. Furthermore, the linear changes observed in the placebo condition for both GTE and SGE (see Fig. 2A & B) suggest that visual scanning naturally stabilises over time, as drivers become more familiar with the traffic environment. Thus, further studies are required to assess the efficacy of gaze entropy measures in detecting alcohol-induced driver impairment across varying levels of traffic complexity and familiarity with the environment.

It is worth noting that the direct interpretability of this study is impacted by some methodological limitations. Although there were no significant interaction effects for the primary variables, the relatively large effect sizes suggest that effects may be detected with a larger sample size. Still, the significant main effects of alcohol despite small sample size and low BrAC reflect the sensitivity of gaze entropy measures and driving performance to alcohol effects. Inclusion of a manipulation check and subjective assessment of intoxication may also have strengthened these results and provided further evidence for the divergence between subjective assessment and objective measures of impairment. Further studies with larger sample size, variable BrAC levels, and controlling for individual variance in drinking and driving experience will provide better understanding of how alcohol compromises visual scanning strategy to impact upon driving performance.

## 5. Conclusion

The results from this study provide preliminary evidence for the influence of alcohol on gaze behaviour. Alcohol's attenuation of top-down or goal-driven gaze control is reflected through significant reduction in GTE across both ascending and descending sessions. The reduction in GTE is also accompanied by SGE increase, which reflects a more scattered viewing behaviour resulting from alcohol intoxication; and these changes in gaze behaviour mediated the impact of alcohol upon driving performance. Further investigations are required to replicate these findings and explore how gaze entropy measures may vary across drinking habits, driving experience and varying levels of scene and driving complexity. Additionally, investigation of these measures in naturalistic settings is required for a more direct assessment of their efficacy in detecting alcohol-induced alteration in gaze behaviour. Accumulating evidence across a broad range of settings and driver characteristics will aid the development of gaze entropy measures into DMS for real-time detection of alcohol-induced impairment to supplement current deterrent strategies that rely on controversial BAC limits to reduce alcohol-related traffic accidents.

## Contributors

BS and LD designed the study protocol. BS was responsible for data collection and processing. All authors were involved in the data analysis and interpretation of results. BS drafted the manuscript. DC and LD provided critical revision of the manuscript prior to submission.

## Declaration of Competing Interest

The authors have no conflict of interest to report.

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