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# Does Cognitive Distraction Improve or Degrade Lane Keeping Performance? Analysis of Time-to-line Crossing Safety Margins

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## Abstract

Studies on the effect of cognitive load (CL) on driving performance suggest that lane keeping performance is improved by cognitive distraction, due to a reduction in measures of the standard deviation of lateral position (SDLP). However, the effect of CL on drivers' lateral control is still not fully understood, and previous studies have shown mixed conclusions regarding the effect of CL on time-to-line crossing (TLC) safety margins. Hence, a driving simulator experiment was performed, requiring performance an auditory-response working memory task (CL task), during driving, presented at of three difficulty levels. Similar to previous studies, CL led to increased micro-steering activity, as well as a diminished SDLP, implying a better lane keeping performance. However, a systematic comparison of TLC calculations showed that the TLC values consistently decreased with the CL task, suggesting a degraded safety margin of lane keeping. While these decreased TLCs did not bring the vehicle close to actual lane departure, they do put into question the general finding that lane keeping is improved by cognitive distraction. We discuss how the increased micro-steering activity could lead to the somewhat counterintuitive simultaneous decrease in both SDLP and TLC. In addition, we suggest the use of a new method for TLC calculations, assuming constant lateral acceleration. We argue that by involving short time windows (3 s~5 s) of chunking, this method may be useful for assessing drivers' safety behaviour, and correct detection of unsafe cognitive distraction.

Keywords: Cognitive distraction; cognitive load; lane keeping; safety margins; time-to-line crossing

## 1. Introduction

Driver distraction and inattention is a common occurrence in everyday driving, and has become a main cause of many vehicle crash accidents. For instance, results from the 100-Car Naturalistic Driving Study showed that approximately 78% of crashes, and 65% of near-crashes, involved driver inattention (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Driver inattention is mainly caused by distraction associated with secondary tasks, driving-related inattention to the forward roadway, non-specific eye glances, and fatigue (Liang & Lee, 2010). Driver distraction is described as "a diversion of attention away from activities critical for safe driving toward a competing activity" (Young, Lee, & Regan, 2008, pp. 34). In the US, distraction-related crashes contributed to ten percent of fatal crashes, eighteen percent of injury crashes, and sixteen percent of all police-reported motor vehicle traffic crashes in 2014 (National Centre for Statistics and Analysis, 2016). Recently, both cognitive and visual distraction have been widely studied, in terms of their impact on drivers' awareness and understanding of the surrounding traffic (Haque & Washington, 2014; Reyes & Lee, 2008; Ross et al., 2014; Sodhi, Reimer, & Llamazares, 2002; Strayer, Watson, & Drews, 2011), vehicle control (Blanco, Biever, Gallagher, & Dingus, 2006; Harbluk, Noy, & Eizenman, 2002; Jamson & Merat, 2005; Muhrer & Vollrath, 2011), and ability to respond to hazards (D Addario, Donmez, & Ising, 2014; Haque & Washington, 2015; Lamble, Kauranen, Laakso, & Summala, 1999).

The effect of visual distraction is clear, in that, increased visual distraction leads to degraded vehicle control (Angell, Auflick, Austria, Kochhar, Tijerina, Biever et al., 2006; Kountouriotis & Merat, 2016; Liang et al., 2010), such as increased lane departures, and higher speed variance. However, the effect of cognitive (non-visual) distraction on driving performance is currently unclear. This term normally refers to an overall withdrawal of attention away from the driving task (i.e. “mind off road”, see Victor, 2005; Engstrom, Markkula, Victor, & Merat, 2017). Studies show mixed findings regarding the effect of cognitive distraction on driving performance. On the one hand, cognitive distraction is shown to diminish drivers’ perceptual ability to detect targets (Haque & Washington, 2014; Reyes & Lee, 2008) and also increase drivers’ response time to hazards (Horberry, Anderson, Regan, Triggs, & Brown, 2006; Lamble et al., 1999; Strayer & Drews, 2004). These findings seem to implicate that cognitive distraction impairs driving performance.

On the other hand, many studies indicate that cognitive distraction leads to a reduction in the vehicle’s standard deviation of lateral position (SDLP), but there is currently a divergence in views regarding whether such reductions should be interpreted as impaired (Mehler, Reimer, Coughlin, & Dusek, 2009; Reimer, 2009) or improved (Engström, Johansson, & Östlund, 2005; He, McCarley, & Kramer, 2014; He & McCarley, 2011; Jamson et al., 2005; Kaber, Liang, Zhang, Rogers, & Gangakhedkar, 2012; Kountouriotis & Merat, 2016; Liang et al., 2010; Son, Lee, & Kim, 2011) driving performance. In addition, studies have found this reduction in SDLP to be accompanied by a higher gaze concentration towards the road centre (Cooper, Medeiros-Ward, & Strayer, 2013; Victor, Harbluk, & Engstrom, 2005; Wang, Reimer, Dobres, & Mehler, 2014), which is thought to be a possible reason for this reduction in SDLP (Boer, Spyridakos, Markkula, & Merat, 2016; Kountouriotis & Merat, 2016; Liang et al., 2010; Victor et al., 2005), though, again, the relationship between these two particular metrics is not currently understood.

Investigations on drivers’ steering control show that cognitive distraction increases micro-steering activity (Engström et al., 2005; Son et al., 2011), results in higher steering entropy (Boer, Rakauskas, Ward, & Goodrich, 2005; Kountouriotis, Spyridakos, Carsten, & Merat, 2016), increased micro-steering reversal rate, and higher steering wheel acceleration (Kountouriotis et al., 2016). This finding has also been regarded as the direct reason for the diminished SDLP (Engstrom et al., 2017; He et al., 2014). However, it is not currently clear whether the increased steering activity during cognitive distraction is synonymous with good or bad lane keeping performance, although Kountouriotis et al. (2016) state that the increased steering activity is likely to be associated with more careful ‘micro-corrections’.

Although it can be argued that measures outlined above provide a good indication of drivers’ control behaviour during cognitive distraction, there is still a need to identify the correct parameters and methods to understand the effect of cognitive distractions on drivers’ lateral safety margin, and, therefore, whether this activity is likely to impair driving performance. Moreover, both SDLP and steering reversal rate are usually measured using a long time window (normally 30 s or more) (Engstrom et al., 2005; Kountouriotis & Merat, 2016; Liang et al., 2010), which makes these discrete measures unsuitable for the immediate and real-time detection of cognitive distraction. There is, therefore, a need to consider the value of a more continuous parameter, for identifying real-time cognitive distraction.

In terms of drivers' lateral safety control, Time-to-Line Crossing (TLC) is a commonly used parameter (Mammar, Glaser, Netto, & Blosseville, 2004; Östlund et al., 2005; Society of Automotive Engineers, 2015; Van Winsum, de Waard, & Brookhuis, 1999). TLC represents the time available for a driver "until the moment at which any part of the vehicle reaches one of the lane boundaries" (Godthelp, Milgram, & Blaauw, 1984), served as an indication of the safety margin during steering control (Van Winsum et al., 1999). TLC is often used to evaluate driving performance (de Nijs, Mulder, & Abbink, 2014; Green, 2007; Van Winsum et al., 1999), investigate steering control (Godthelp & Konings, 1981; Godthelp, 1986), and predict lane departures (Lee, Kwon, & Lee 1999; Mammar et al., 2004; Mammar, Glaser, & Netto, 2006). Therefore, we argue that TLC may be a good measure for investigating drivers' safety control during cognitive distraction, and that its continuity makes it more suitable for real-time cognitive distraction detection. Previous studies have provided mixed conclusions regarding the effect of cognitive load on TLC. For instance, a series of linked studies from the European HASTE project (Östlund et al., 2004) found a significant change in TLC during cognitively loading task for elderly drivers (over 60 years old), while no significant effect was observed for average drivers (25-50 years old). This may be because TLC is not considered an easy metric to measure correctly (Society of Automotive Engineers, 2015; Mammar et al., 2004; Van Winsum et al., 1999). Therefore, in the present study, we methodically considered different approaches for computing this metric, and are able to show that cognitive load does indeed affect TLC, in a somewhat unexpected way.

## 2. Method

### 2.1 Participants

35 participants were recruited for the experiment. All of them held a valid driving license, for a minimum of 2 years, and had normal or corrected-to-normal vision. A within-subjects design was used for the experiment, but due to simulator sickness and equipment failures, data from only 32 participants (11 females and 21 males) are reported here. Participants were aged between 21 and 62 years (mean=33.5 years, SD=13.6 years), with an average driving experience of 52000 km (SD = 45850 km). They were paid 120 RMB for the whole experiment, which included 4 drives with different driving and secondary tasks. This study reports on a car following scenario with a secondary cognitive task.

### 2.2 Apparatus

The experiment was conducted in a 6 degree-of-freedom motion-based driving simulator in the State Key Laboratory of the Automotive Safety and Energy, at Tsinghua University, China (see Fig. 1). This high fidelity simulator consists of a complete car with working control and motion platform surrounded by three front-view screens, which are positioned 2.7 m in front of the car, providing 200 degrees horizontal and 50 degrees vertical view. Two rear-view screens provide a 36 degrees horizontal and 30 degrees vertical view of the rear, through the rear-view mirror. The car was refitted from a BMW3 Series car with real brake, steering wheel, accelerator, automatic gearshift and indicators inside. The 6 degree-of-freedom motion platform below the car provides an accurate feeling of acceleration/deceleration and cornering. Driving data were recorded data at 60 Hz. In addition, SensoMotoric Instruments (SMI) eye tracking glasses collected eye movement data at 30 Hz.

Fig. 1． Six DOF Motion-based Driving Simulator

## 2.3 Driving environment

The driving scenario was a car following situation on a straight, four-lane urban road comprised of two vehicle lanes, one bicycle-lane, and one sidewalk, in each direction. All lanes were 3.5 m wide, with traffic lights at each intersection. Each intersection was located 3 km away from the next, and the speed limit of the road was 70 km/h. Participants were asked to drive as they would normally, and a lead vehicle, which was traveling at a constant speed of 55 km/h, at a comfortable distance. The traffic lights at the intersections were always green, to allow smooth and continuous driving by participants. There was a steady stream of traffic flow in the adjacent lanes, allowing the simulation of a typical urban driving environment.

## 2.4 Secondary tasks

To investigate the influence of cognitive distraction on driving performance, a working memory task was used as a secondary task during driving. This was the n-back task, first introduced in similar driving experiments by researchers at MIT Agelab (Mehler, Reimer, & Coughlinm, 2012; Reimer, 2009). The task requires participants to respond verbally to a delayed digit recall task, and was presented here at three levels of difficulty: 0-back was the easiest level, which requires participants to immediately repeat aloud the number presented. For the medium difficulty level (1-back), participants were required to recall the number one back in the sequence; and for the high difficulty level (2-back), participants were required to recall the number two back in the sequence.

At the start of the task, a message announcing: “0 (or 1, 2)-back task begins now” was presented, after which 10 digits were presented in turn, at a rate of one every 2.25 s, producing a total task length of 34 s.

## 2.5 Experiment design

A within-participant design was used, with all participants completing three repetitions of each level of n-back during their drive (plus baseline driving, without a secondary task). Participants completed a 15-min drive, where the four independent factors (baseline, 0-back, 1-back and 2-back) were randomly presented. The cognitive tasks always appeared on the parts of the road without an intersection. In addition, the interval between every two contiguous distraction tasks was longer than 1 km so that participant had enough time to recover after each task.

## 2.6 Procedure

The whole experiment contained 4 drives, lasting 120 minutes, altogether. For the first two drives, participants completed a cognitive and visual secondary task. Both drives involved a car following scenario, with half of the participants completing the cognitive task during their first, and vice versa.

After arriving at the laboratory, participants were told that their driving behaviour would be examined in this experiment and they would complete a training and four experiment drives. Then, they practiced the n-back task, which took approximately 10 minutes. After that, participants were introduced to the driving simulator, and were provided with around 15 minutes' training of the control, including familiarity with the steering, accelerating and decelerating of the driving simulator, following of the lead vehicle and also driving whilst engaged in the secondary tasks. After the training and a short break, the participants were equipped with eye tracking glasses, conducting experiment drives continuously. At the end of the experiment, participants completed a questionnaire regarding their basic personal details, were debriefed about the study and received compensation for taking part.

## 2.7 Data analysis

In the present study, we calculated SDLP, steering reversal rates at $0.5^o$ (SRR$0.5^o$) and TLC, to investigate lane keeping performance during cognitive distraction. The lateral position was recorded as a deviation from the centre of lane with left side as positive direction, therefore, SDLP was computed as the standard deviation of vehicle's lateral position. Steering reversal rate measures the number of times the steering wheel changes its direction by a set angle per minute (Kountouriotis et al., 2016; Macdonald & Hoffmann, 1980; Marrkula & Engström, 2006). Gaze concentration was measured by standard deviation of yaw gaze angle to study drivers' eye movement during the cognitive load task (Kountouriotis et al., 2016; Wang et al., 2014), where, low-quality gaze data automatically filtered by SMI eye tracking glasses, and gaze points belong to blink event were excluded. Recent research suggests that a $0.5^o$ angle of steering reversal rate is sensitive to cognitive load (Kountouriotis et al. 2016), representing micro-steering activity during performance of such tasks.

TLC is defined as the distance to line crossing (DLC) along the vehicle's future path, divided by the vehicle speed (Glaser, Mammar, Netto, & Lusetti, 2005; Godthelp et al., 1984; Godthelp et al., 1981; Mammar et al., 2006; Van Winsum, Brookhuis, & de Waard, 2000). This metric was calculated according to the real road profile and curved vehicle trajectory (Mammar et al., 2006), serving as the reference Method 1 in the present paper. However, this method is usually not easy to conduct, due to the limitations of vehicle state variables, vehicle trajectory prediction and lane geometry (Mammar et al. 2004, 2006). Therefore, we also used three approximated methods for deriving TLC, in order to identify an easier and suitable method for investigating the effect of cognitive distraction on vehicle lateral control, as follows (see also Appendix):

Method 2: Assuming constant lateral acceleration (Godthelp et al., 1981; Mammar et al. 2006).

Method 3: Approximated method for assuming constant lateral acceleration (de Nijs et al., 2014; Van Winsum et al., 2000), also mentioned as Acceleration Method in Society of Automotive Engineers (2015).

Method 4: Assuming constant velocity (Lee et al., 1999; Van Winsum et al., 2000), also mentioned as Velocity Method in Society of Automotive Engineers (2015);

As will be further presented below, Method 2 generally provides a very good approximation and similar sensitivity to cognitive load as Method 1, whereas Methods 3 and 4 do not. A typical calculation of TLC with Method 2, derived during a secondary task phase, is shown in Fig. 2. Lateral velocity is the derivative of lateral position, and lateral acceleration is the derivative of lateral velocity (i.e., lateral velocity and acceleration in the road reference frame, not the vehicle reference frame). TLC peak and trough areas correspond to the null point and peak area of lateral acceleration, respectively. In this representative example, we can see lower SDLP, more TLC peaks, and lower TLC troughs appearing during the cognitive task, compared to baseline.

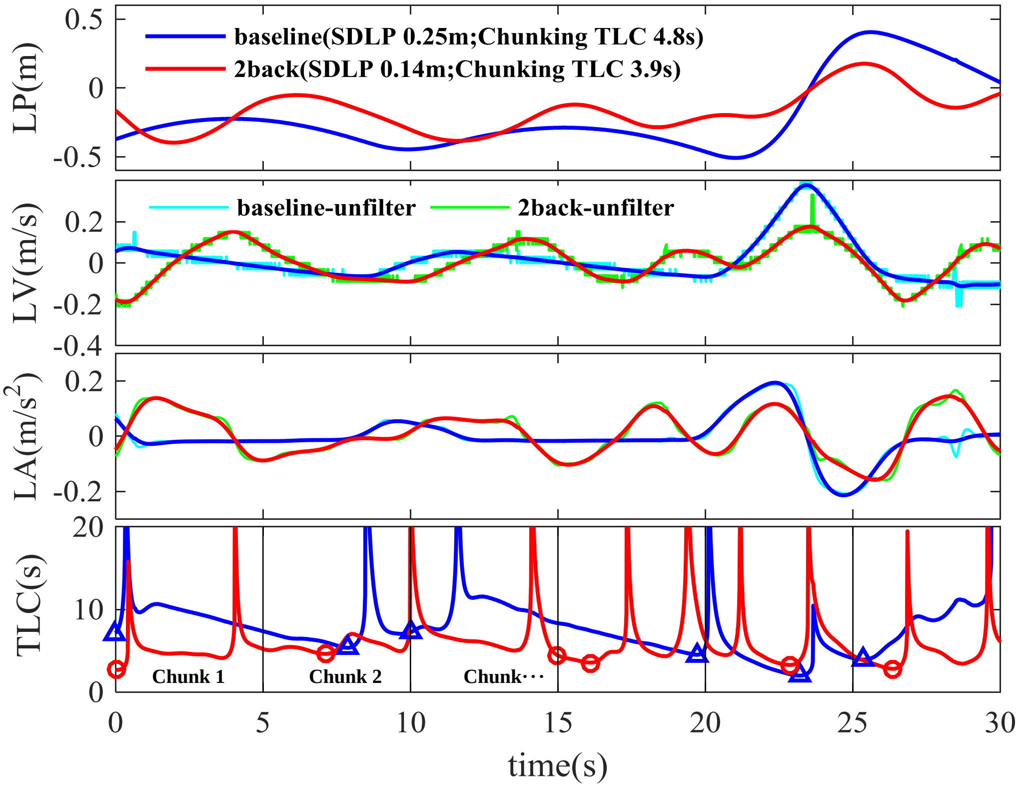

Fig. 2. Two typical examples of lane-keeping during baseline driving and with the 2-back task. LP: lateral position. LV: lateral velocity. LA: lateral acceleration. TLC: time-to-line crossing. The red circles and blue triangles represent minimum TLC in corresponding chunks (i.e., see chunking method below) for 2-back and baseline respectively.

A repeated measures general linear model was used to analyses the data (SPSS v.20). The effect of cognitive distraction on lateral control was evaluated using a 4 within-participant (baseline driving, driving with 0-back, 1-back, and 2-back) design, with $p<0.05$ as a statistical significance, and partial eta squared representing the effect size (Cohen J., 1969, pp. 278-280; Richardson, J. T., 2011). In addition, post hoc comparisons of paired means were used to compare the significant difference between two levels of variables, when the main effects appeared to be significant.

Since the percentage correct of each level of the cognitive task was seen to cluster near 100%, making its distribution negatively skewed, the Friedman and Wilcoxon rank tests (Friedman, 1937; Wang et al., 2014) were used for analyzing the performance of the n-back task.

## 3. Results

### 3.1 Secondary task performance

There was a significant main effect of task demand on the percentage of correct responses ($\chi^2_{(df=2)}=17.365$, $p<0.001$, Friedman test), with a ceiling effect seen on performance (0-back: 100%; 1-back: 96.2%; 2-back: 94.7%). However, more errors occurred for the more difficult tasks (0-back vs. 1-back: $p<0.001$, 0-back vs. 2-back: $p=0.002$, Wilcoxon rank tests).

### 3.2 Driving performance

In line with previous studies, the effect of the n-back cognitive task on driving performance was observed using SDLP, SRR0.5$^{o}$, gaze concentration and also, for the first time, four different versions of TLC, as described above.

SDLP: There was a significant main effect of task demand ($F(3, 93)=7.165$, $p<0.001$, $\eta_p^2=0.188$) on SDLP, as shown in Fig. 3 (left). Post-hoc comparisons with Bonferroni adjustments showed that the difficult cognitive task (2-back) produced lower SDLP than baseline ($p=0.007$), and almost approached significance ($p=0.065$) when compared to low cognitive task (0-back). SDLP during the 1-back task was only found to be lower than baseline ($p=0.035$). This finding shows that, in line with other studies, the cognitive load task causes a systematic reduction in lateral deviation, as measured by SDLP (Cooper et al., 2013; Herbert et al., 2016; Jamson et al., 2005; Kountouriotis & Merat, 2016).

SRR0.5$^{o}$: There was a significant main effect of task demands on SRR0.5$^{o}$ ($F(3, 93)=12.976$, $p<0.001$, $\eta_p^2=0.295$) , as shown in Fig. 3 (right). Post-hoc comparisons with Bonferroni adjustments showed higher SRR0.5$^{o}$ during the 2-back task, than both baseline ($p<0.001$) and low cognitive load (0-back) task ($p=0.005$). The 1-back task produced higher SRR0.5$^{o}$ values than both baseline ($p=0.002$) and the low cognitive (0-back) task ($p=0.019$). This indicates drivers tend to take more micro-steering movements when engaged in a cognitive load task, and this type of activity increased with the level of cognitive load. This finding was also consistent with results from previous studies (Engström et al., 2005; Son et al., 2011).

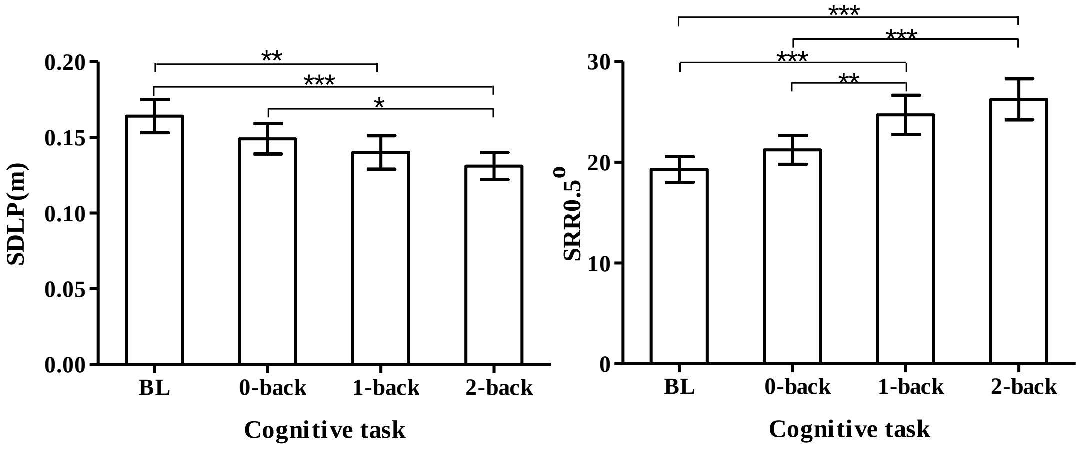

Fig. 3. Standard deviation of lateral position (SDLP- left) and steering reversal rate 0.5° (right), Error bar = SEM. * p<0.1, ** p<0.05, *** p<0.01. BL: baseline.

Gaze concentration: There was a significant main effect of task demand (F(2.23, 55.8) =8.093, p=0.001, $\eta_p^2$=0.245) on gaze concentration, as shown in Fig. 4. Post-hoc comparisons, with Bonferroni adjustments, showed lower standard deviation of yaw gaze angle during 2-back, compared to both baseline (p=0.011) and the low cognitive load (0-back) task (p=0.034). The 1-back task also produced lower standard deviation of yaw gaze angle than both baseline (p=0.008) and low cognitive load (0-back) task (p=0.021). This result shows that, in line with other studies, drivers tend to concentrate their visual attention towards the forward road centre during a cognitive load task (Cooper et al., 2013; Wang et al., 2014).

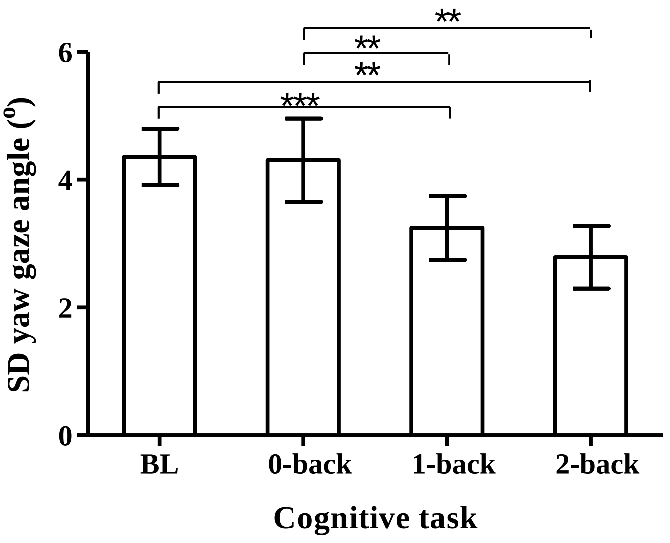

Fig. 4. Standard deviation of yaw gaze angle, Error bar = SEM. * p<0.1, ** p<0.05, *** p<0.01. BL: baseline.

3.3 Time-to-line crossing (TLC)

A chunking method was used to measure TLC safety margins, by averaging the minimum TLC across short consecutive chunks of the data, instead of the minimum TLC during the whole task. This method is similar to the mean of minima method used in HASTE (Engström et al., 2005; Östlund et al., 2005) but easier to calculate, and more robust, as illustrated below.

This chunking method is a procedure which divides data into equivalent, elementary, chunks of data, to facilitate a robust and consistent calculation of parameters (Dozza, Bärgman, & Lee, 2013). In the present study, we divided the long task phase data (34 s) into shorter chunks, with a time window of 5 s; then calculated the corresponding minimum TLC in each time window. The minimum TLC of each chunk was then averaged to provide the safety margin for the whole task phase, with a higher mean of minimum chunking TLC, representing a higher safety margin. For example, a 5 s time window would produce 7 segments (see Fig. 2).

A repeated measures ANOVA on this mean of minimum chunking TLC (calculated using Method 2, see below) showed a main effect of task (F(3, 87)=3.288, p=0.024, $\eta_p^2$=0.102), as shown in Fig. 5. Post hoc comparisons with Bonferroni adjustments showed a significant difference between high cognitive load task and baseline (p=0.039), with a lower mean of minimum chunking TLC during the 2-back task (Mean= 5.40 s), compared to baseline (Mean= 6.14 s). Although this value is significantly lower than baseline, and suggests relatively lower levels of safety during the more demanding 2-back task, it is not necessarily associated with a dangerous lane departure, in the context of this driving simulator study.

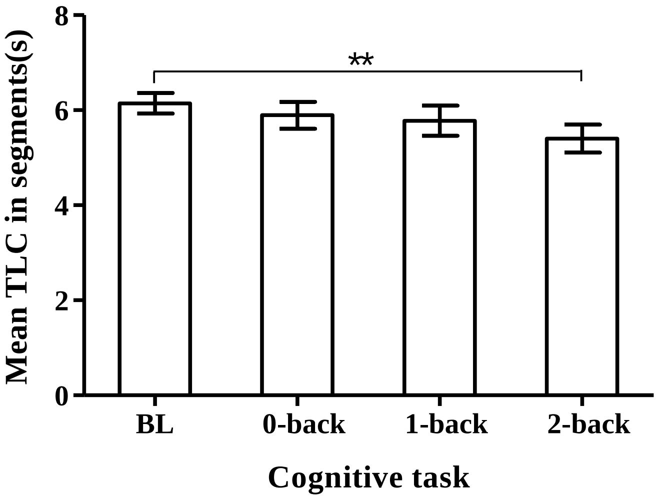

Fig. 5. Mean of minimum TLC in 5s time windows. Error bar = SEM. * p<0.1, ** p<0.05, *** p<0.01. BL: baseline.

To verify this finding, analyses of variance were conducted on the chunked TLC values for all four calculation approaches (Table 1). The results showed that mean of minimum chunking TLC was lower during the cognitive task, compared to baseline, and especially so during the high cognitive load, 2-back, version of the task. A significant level of 0.05 was reached for TLC calculations using both Method 1 and Method 2. Although not all differences were significantly different, this finding shows a promising technique for real-time identification of cognitive distraction during driving.

**Table 1. Comparison of different calculations for TLC (* p<0.1, ** p<0.05, *** p<0.01)**

| Method | M(SE) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **baseline** | **0-back** | **1-back** | **2-back** | **F(3,87)** | **P** | **host poc** |
| **Method 1** | 5.75(0.22) | 5.52(0.28) | 5.51(0.29) | 5.05(0.25) | 2.673 | 0.052 | BL vs.2back** |
| **Method 2** | 5.77(0.21) | 5.46(0.26) | 5.37(0.29) | 5.01(0.27) | 3.288 | 0.024 | BL vs.2back** |
| **Method 3** | 10.82(0.61) | 10.06(0.70) | 10.35(0.75) | 9.95(0.88) | 0.679 | 0.567 | No Significance |
| **Method 4** | 13.59(0.87) | 12.92(0.86) | 13.42(0.78) | 12.68(1.06) | 0.562 | 0.641 | No Significance |

To further investigate the robustness of these calculations, and determine the most suitable time window for the chunking method, we varied the time windows from 3 s to 9 s with an interval of 2 s between chunks, and then compared results, which showed that the chunking TLC decreased with a cognitive load for all of the time windows used, as shown in Table 2, although the 3 s and 5 s time windows were perhaps the most powerful for illustrating the effects.

**Table 2. Comparison of different time window for chunking TLC (based on Method 2, * p<0.1, ** p<0.05, *** p<0.01)**

| Time window | M(SE) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **baseline** | **0-back** | **1-back** | **2-back** | **F(3,87)** | **P** | **host poc** |
| **3 s** | 6.51(0.24) | 6.22(0.29) | 6.03(0.32) | 5.65(0.29) | 3.601 | 0.017 | BL vs.2back*** |
| **5 s** | 5.77(0.21) | 5.46(0.26) | 5.37(0.29) | 5.01(0.27) | 3.288 | 0.024 | BL vs.2back** |
| **7 s** | 5.35(0.18) | 5.03(0.23) | 4.99(0.29) | 4.62(0.24) | 2.573 | 0.059 | BL vs.2back* |
| **9 s** | 4.89(0.18) | 4.71(0.22) | 4.74(0.29) | 4.41(0.24) | 1.632 | 0.188 | No significance |

## 4. Discussion and Conclusions

The aim of the current study was to further understand how drivers' lane keeping performance is affected by concurrent performance of a demanding non-visual task. Previous studies have provided conflicting views on the effect of such tasks on some lateral control measures. Although there is near-universal agreement that there is a reduction in SDLP with increasing difficulty of the non-visual task, there is some disagreement in the literature on whether this reduction in lateral control and accompanying changes in steering control are synonymous with improved or degraded safety margins. Here, three difficulty levels of cognitive task were presented to drivers in a simulator study, and different measures of lane keeping performance were analyzed. In line with previous research (Cooper et al., 2013; Herbert et al., 2016; Jamson et al., 2005; Kountouriotis & Merat, 2016), a lower SDLP was observed with concurrent cognitive load, in addition to an increase in steering reversal rate (at the $0.5^o$ level) and gaze concentration, with both measures showing a systematic change with increasing cognitive load.

However, we argue that TLC has a higher face validity as a measure of lateral safety margins than SDLP, since SDLP represents the stability of lane keeping, which is an indirect factor of lane keeping safety, while TLC is more straightforward, representing the remaining time to an actual lane departure. Therefore, we investigated the effect of this cognitively loading task on TLC. Previous studies have shown that visual distraction leads to both an increased SDLP and a decreased TLC safety margin (Engström et al., 2005; Metz & Krüger, 2011) in terms of mean of TLC minima, and percentage of TLC less than 1s, which was also observed consistently in our study. However, we also demonstrate, for the first time, that TLC safety margins decrease with cognitive distraction, an effect that is statistically significant when using correct mathematical definitions of TLC, and a chunking analysis method.

To our knowledge, only a handful of studies have focussed specifically on examining TLC values during cognitive distraction, and when TLC results have been reported, these have generally been non-significant. For example, studies from the HASTE project (Carsten & Brookhuis, 2005) showed a significant effect of cognitive distraction for elderly drivers, with a significantly higher mean of TLC minima during engagement in low levels of cognitive distraction (compared to both baseline and moderate levels of cognitive distraction), but they failed to find a significant effect of cognitive distraction for average drivers, see also Östlund et al. (2004); and Herbert et al. (2016). Indeed, our calculations of mean TLC, minimum TLC, mean of TLC minima, and percentage of TLC less than 1s also failed to find any significant differences between baseline and task data, in the present study. Our results suggest that the main reason for non-significance differences in previous studies might be the use of inexact approximations of the continuous TLC signal (like Methods 3 and 4) and insensitive summary metrics of TLC. At first glance, it would seem that our chunking method and the mean of TLC minima are rather similar. Looking at examples like that in Fig. 2, a possible explanation of the better sensitivity of the chunking method is that it also picks up on the increased frequency of TLC minima with cognitive load; note that even though the TLC minima are in a roughly similar range between baseline and cognitive load, the baseline signal spends more time at higher TLC values, something which can be picked up by the chunking method, but not the mean of minima method.

From a driving safety perspective, our results create an interesting tension between the reduced SDLP, suggesting safer lane keeping performance during cognitive distraction, and the reduced TLC safety margins, suggesting reduced safety. This provides an important further nuance to the general debate about the effects of cognitive load on traffic safety. Previously, it has been argued that cognitive load might lead to improved lane keeping performance (Engström et al., 2005; He et al., 2014; Liang et al., 2010; Son et al., 2011), but our results make such a conclusion less clear. It might be that the worse TLC is more important for safety than the improved SDLP, but the opposite might just as well be true, and it should be noted that the observed TLC values were not low enough in this study to take the vehicle close to actual lane departure (occurring at TLC=0). We argue that a full implication of such reduced TLCs on actual safety can only be fully evaluated by observing actual crash/near crash data and lane departure rates, for instance by using results from Naturalistic Driving Studies.

The present findings on TLC could also be useful in the context of trying to understand the mechanisms behind how cognitive load affects driving, in general, and lane keeping, in particular. It has been previously argued that the reduced SDLP with cognitive load is mediated by the increased micro-steering activity (Engstrom et al., 2017; He et al., 2014; Kountouriotis et al., 2016). Such an interpretation would seem consistent with our observations here: Again considering examples like the one in Fig. 2, the increased steering activity might be interpreted as a more engaged lane-keeping activity, correcting the lateral movement more often, and more aggressively, causing the vehicle to stay within a narrower range of lane positions (i.e., with reduced SDLP) but with more pronounced lateral weaving within that range (causing the reduced TLC). If this is a general feature of lane-keeping under cognitive load, it might be observable also in metrics of lateral speed and acceleration. Therefore, data for both the lateral absolute speed and the lateral absolute acceleration values were analyzed. These follow-up analyses showed that lateral absolute speed was not affected by cognitive load, but that lateral absolute acceleration (F(3, 87)=3.251, p=0.026, $\eta_p^2$=0.101) was significantly affected by cognitive load. Post hoc comparisons with Bonferroni adjustments showed that lateral absolute acceleration was higher in the high cognitive task (M=0.036, SE=0.003) than during baseline (M=0.030, SE=0.002), approaching significance (p=0.061), as shown in Fig. 6. In other words, the lateral acceleration data are consistent with the hypothesis presented above, suggesting that cognitive load leads to a more engaged or assertive lane keeping.

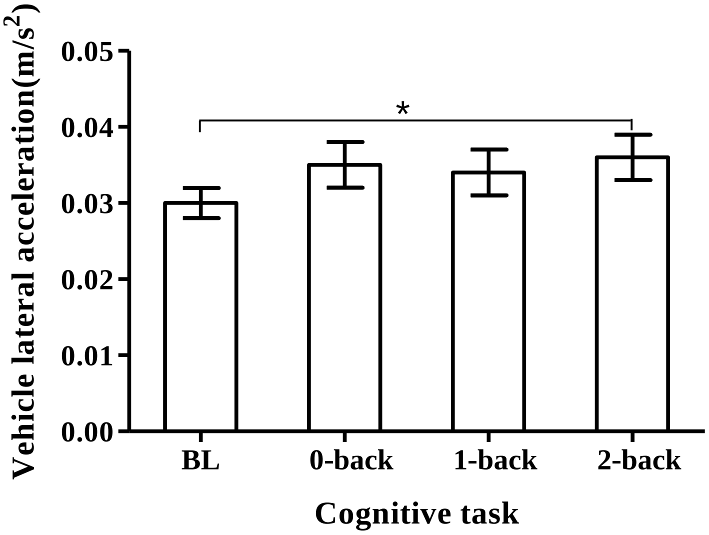

Fig. 6. Vehicle lateral acceleration. Error bar = SEM. * p<0.1, ** p<0.05, *** p<0.001. BL: baseline.

For potential applications such as assessing safety behaviour and identifying cognitive distraction, TLC has long been recognized as an indicator of safety margins (Society of Automotive Engineers, 2015; Östlund et al., 2005; Van et al., 1999). Our calculations show, for the first time, that Method 2 (Assuming constant lateral acceleration method) provides a better approximation of the definition (Method 1) than both Method 3 and Method 4. Also, Method 2 does not require data on road profiles and vehicle dynamic parameters, making it easier and more accessible for calculating TLC, than Method 1. In addition, the finding that a 3 s time window chunking TLC was significantly lower than baseline during the 2-back cognitive task, suggests that TLC could be useful as a continuous real-time measure of cognitive load. The SDLP and steering reversal rate metrics are less amenable to this type of chunking with short time windows. Indeed, these metrics are usually calculated with 30 s time window data (Engstrom et al., 2005; Liang et al., 2010). This may because one period of a vehicle's lateral position lasts around 8 s, and steering reversals are discrete events occurring with low frequency. Thus, a long time window is necessary for capturing changes. However, the 3 s chunked TLC does not seem to be as sensitive as SDLP or steering reversal rates for distinguishing between different levels of cognitive load, only showing a difference between baseline driving and the most difficult version of the task. In summary, our results show that TLC calculation Method 2, with a short time window (3 s~5 s) chunking may be a suitable metric for assessing or detecting drivers' safety behaviour and cognitive distraction; it is as effective in detecting cognitive load as the more exact Method 1, but less complex and computationally demanding. We encourage further studies in this area to confirm our findings.

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## Appendix

Four methods for TLC calculation are shown in Table 3. Methodologically, Method 2 is a simplification of Method 1 regarding $\varphi_L$ near 0; Method 3 is a simplification of Method 2 regarding $TLC$ near 2s; Method 4 is a simplification of Method 3 regarding $LA$ near 0. For lane keeping in straight road, front tire relative yaw angle $\varphi_L$ is near 0, so the result from Method 2 is close to method 1.

Table 3(a). Formulations for TLC calculation

| **Method** | **Abbrevation** | **Formulation** | **TLC** | **Additions** |
|---|---|---|---|---|
| Method 1 | Trigonometric Computation Method | $TLC_{left1} = \frac{R\cdot(cos^{-1}\left(cos\varphi_L - \frac{LP_{left}}{R}\right) - \varphi_L)}{u}$<br>$TLC_{left2} = -\frac{R\cdot(cos^{-1}\left(cos\varphi_L - \frac{LP_{left}}{R}\right) + \varphi_L)}{u}$<br>$TLC_{right1} = \frac{R\cdot(cos^{-1}\left(cos\varphi_L - \frac{LP_{right}}{R}\right) - \varphi_L)}{u}$<br>$TLC_{right2} = -\frac{R\cdot(cos^{-1}\left(cos\varphi_L - \frac{LP_{right}}{R}\right) + \varphi_L)}{u}$ | The minimum positive value of the 4 formulations | $LP_{left} = \frac{W_{lane} - W_{vehicle}}{2} - y$<br>$LP_{right} = -\frac{W_{lane} - W_{vehicle}}{2} - y$<br>$R = u/\dot{\varphi}$<br>$\varphi_L = \varphi + \delta_f$<br>TLC is undefined for the following conditions: (1) $LP_{left} < 0$, or $LP_{right} > 0$ (outside of lane); (2) LA=0(Method 2), LV=0(Method 3), LA+LV=0(Method 4). |
| Method 2 | Assuming constant lateral acceleration | $\frac{1}{2}LA\cdot TLC_{left}^2 + LV\cdot TLC_{left} = LP_{left}$<br>$\frac{1}{2}LA\cdot TLC_{right}^2 + LV\cdot TLC_{right} = LP_{right}$ | The minimum positive root of the 2 equations | |
| Method 3 | Approximated method for assuming constant lateral acceleration | $TLC_{left} = LP_{left}/(LV + LA)$<br>$TLC_{right} = LP_{right}/(LV + LA)$ | The minimum positive value of the 2 formulations | |
| Method 4 | Assuming constant velocity | $TLC_{left} = LP_{left}/LV$<br>$TLC_{right} = LP_{right}/LV$ | The minimum positive value of the 2 formulations | |

Table 3(b). Definitions of parameters

| Symbol | Definition | Units |
|---|---|---|
| $TLC_{left/right}$ | Time to Line(left/right) Crossing | s |
| $y$ | Vehicle lateral position | m |
| $LP_{left}$ | Vehicle lateral distance to left line (vector) | m |
| $LP_{right}$ | Vehicle lateral distance to right line (vector) | m |
| $W_{lane}$ | Lane width | m |
| $W_{vehicle}$ | Vehicle front tread | m |
| $R$ | Vehicle turning radius (vector) | m |
| $u$ | Vehicle speed | m/s |
| $\varphi$ | Vehicle yaw | radians |
| $\dot{\varphi}$ | Vehicle yaw rate | rad/s |
| $\delta_f$ | Steering angle | radians |
| $\varphi_L$ | Front tire relative yaw angle | radians |

**Coordination system:** (1) x-coordinate: center of lane with vehicle front as the positive direction; (2) y-coordinate: vertical of lane center with left as the positive direction; (3) for all angle parameters, anticlockwise as the positive direction.

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