Transportation Research Part F 43 (2016) 315–324

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Obstacle avoidance under automated steering: Impact on driving and gaze behaviours

J. Navarro [a,*], M. François [a,b], F. Mars [c]

[a] EMC (Laboratoire d'étude des mécanismes cognitifs), University of Lyon 2, France
[b] Volvo Group Trucks Technology (GTT), Saint Priest, France
[c] IRCCyN (Institut de Recherche en Communication et en Cybernétique de Nantes), CNRS (French National Research Center) and UNAM, France

ARTICLE INFO

Article history:
Received 10 November 2015
Received in revised form 17 May 2016
Accepted 3 September 2016
Available online 14 September 2016

Keywords:
Lateral control delegation
Eye movement patterns
Driving assistance
Automatic steering
Vehicle control

ABSTRACT

Within the context of more and more autonomous vehicles, an automatic lateral control device (AS: Automatic Steering) was used to steer the vehicle along the road without drivers' intervention. The device was not able to detect and avoid obstacles. The experiment aimed to analyse unexpected obstacle avoidance manoeuvres when lateral control was delegated to automation. It was hypothesized that drivers skirting behaviours and eye movement patterns would be modified with automated steering compared with a control situation without automation. Eighteen participants took part in a driving simulator study. Steering behaviours and eye movements were analysed during obstacle avoidance episodes. Compared with driving without automation, skirting around obstacles was found to be less effective when drivers had to return from automatic steering to manual control. Eye movements were modified in the presence of automatic steering, revealing further ahead visual scanning of the driving environment. Resuming manual control is not only a problem of action performance but is also related to the reorganisation of drivers' visual strategies linked to drivers' disengagement from the steering task. Assistance designers should pay particular attention to potential changes in drivers' activity when carrying out development work on highly automated vehicles.

1. Introduction

The growing use of motor vehicles is associated with mortality, injuries, and economics issues related to crashes (Najm, Smith, & Yanagisawa, 2007). Human errors are involved in 93% of road accidents (NHTSA, 2008). Several means of action are implemented to reduce accidents numbers and consequences. Passive safety, driver's sensitization, prevention, and repression are already widely introduced. Besides, the potential development of active safety is great. Driving assistances and driving automation has therefore been a contemporary concern in the last decades. Driving assistances already tend to replace drivers in various driving subtasks (e.g. speed control with Adaptive Cruise Control – ACC). Among driving assistances devices, lateral control assistances aim to prevent lane departures. In 2013, the Fatal Analysis Reporting System (FARS) estimates that roadway departure crashes represent about 56% of road fatalities in the United States.

Various types of assistances devices were designed to assist lateral control. Navarro, Mars, and Young (2011) proposed a classification of those devices based on the combination of two human-automation interaction frameworks (Hoc, Young, &

* Corresponding author at: Université de Lyon 2, 5 avenue Pierre Mendès France, F 69676 Bron cedex, France.
E-mail address: Jordan.Navarro@univ-lyon2.fr (J. Navarro).

http://dx.doi.org/10.1016/j.trf.2016.09.007
1369-8478/

Blosseville, 2009; Young, Stanton, & Harris, 2007). Some types of systems have already been implemented in real cars, such as electronic stability control, which acts on the vehicle dynamics with minimal feedback to the driver, or lane departure warning systems, which provide interpreted information to improve the driver's situation diagnosis. More recently, solution have been proposed to interact with the driver through the steering wheel, either punctually in critical situations (the motor/haptic priming approach, see Deroo, Hoc, & Mars, 2012; Deroo, Hoc, & Mars, 2013; Navarro, Mars, Forzy, El-Jaafari, & Hoc, 2010; Navarro, Mars, & Hoc, 2007) or in a continuous way (the shared control approach, see Abbink, Mulder, & Boer, 2012; Mars, Deroo, & Charron, 2014; Mars, Deroo, & Hoc, 2014; Mulder, Abbink, & Boer, 2012). The next and final step will be to achieve function delegation in which lateral control is completely delegated to automation. In that case, the device controls the lateral dimension of the trajectory autonomously and the driver becomes a supervisor of this function. This type of automation is referred as Automatic Steering (AS).

If both lateral and longitudinal control are delegated to automation the assistance is often referred as highly automated driving that might constitute a fully autonomous vehicle (Merat & Lee, 2012). Since the early 2000's impressive progresses in vehicle-based technology have been made (Markoff, 2010; Thrun et al., 2007) to such an extent that Volvo Cars announced a fleet test of "self driving cars" on public roads by 2017 (Volvo Cars., 2013). However full automation in everyday traffic is not effective yet (van Paassen, 2010). Indeed, the driving environment is not completely predictable and drivers' supervision of the delegated tasks (vehicle control) is still required at some point. Within this context a key question is to assess drivers behaviours when resuming control from a highly automated vehicle is required.

Resuming lateral control from automation that replaces drivers (lateral and longitudinal control automated) at regular intervals or if drivers looked more than 10 s away from the road, took drivers about 35–40 s. Better driving performances were observed after a fixed period of time compared to automation disengagement when drivers looked away from the road for too long (Merat, Jamson, Lai, Daly, & Carsten, 2014). Another simulator study with an assistance replacing both lateral and longitudinal control reported deleterious effects of automation on driving performances only when drivers' attention was diverted by a distracting secondary task. Without secondary task drivers were able to respond effectively to changes to a critical incident by reducing speed in a similar way in manual and automated drives (Merat, Jamson, Lai, & Carsten, 2012). It is important to note however that drivers are likely to engage in non-driving tasks with function delegation automation and that situation awareness deteriorates when they do so (de Winter, Happee, Martens, & Stanton, 2014). In a test track experiment, Hoc et al. (2006) studied avoidance manoeuvres with AS when unexpected obstacles appeared on the road. The AS device was designed to keep the car within the driving lane took it onto a collision course with the obstacle. Drivers were instructed to skirt around obstacles when necessary. In comparison with manual steering, obstacle skirting was carried out with greater steering amplitude and with shorter skirting duration. Those modifications tend to indicate more abrupt responses with AS and have been interpreted as an indicator of difficulties in returning to manual control when required. Confirming earlier data where AS led to an increase in collision frequency due to a sudden braking of a lead vehicle, although less than half than that was observed with ACC (Stanton, Young, Walker, Turner, & Randle, 2001).

Lateral and longitudinal control tend to be considered as two separate dimensions. But, apart for being controlled through different controls (steering wheel or pedals), the two dimensions should rather be considered as closely linked the one with the other. Negotiating a bend for instance appears to rely mostly on lateral control but the vehicle speed is also a key element. Indeed, negotiating the same bend at two different speeds will impact on lateral control. Both lateral and longitudinal control function delegation increase willingness to shift attention from driving to non-driving tasks (Carsten, Lai, Barnard, Jamson, & Merat, 2012). Interestingly delegating lateral control to automation is not equivalent to delegating longitudinal control. Lateral control delegation is much closer to full automation with drivers being less attentive to the road and traffic than longitudinal control, whereas longitudinal control delegation is closer to manual driving (Carsten et al., 2012). Delegating only one dimension of vehicle control or both (i.e. lateral and longitudinal control) may have different effects on driving behaviours when resuming manual control is needed. Under longitudinal control delegation only, drivers were found better at handling automatic deceleration failures compared to both longitudinal and lateral control delegation (Strand, Nilsson, Karlsson, & Nilsson, 2014). But a similar comparison showed no significant differences between ACC alone or combined with AS in terms of reaction times to a breaking event (Larsson, Kircher, & Andersson Hultgren, 2014).

In any case, when part of the control is delegated to automation, the human may face the "out of the loop" phenomenon. When drivers are not in the control loop of vehicle steering and speeding, their awareness of the situation and the assistance states may be reduced (Kaber & Endsley, 1997). Drivers are expected to be more and more "out of the loop" and less and less effective with an increasing delegation of vehicle control to automation (Strand et al., 2014). In an attempt to keep drivers into the driving loop as well as delegating important part of driving to automation, lateral control was delegated to automation whereas drivers remained in control of the vehicle speed. Lateral control delegation was selected because it is closer to full automation from drivers perspective (Carsten et al., 2012). Although this type of assistance (i.e. partial control delegation) might be surprising at the first glance it have already been implemented on real cars. When using ACC, drivers delegate both the cruise speed and the time headway to a lead vehicle to automation. Under usual circumstances, drivers do not have to slow down the vehicle. ACC is taking good care of the vehicle speed for instance when the lead vehicle gently brakes. However, drivers remain responsible to brake in case of an emergency braking because in that particular case ACC will not brake the car. Even closer to the lateral control delegation considered, the park4U® assistance device developed by Valeo takes control of the steering wheel during a parallel or a perpendicular parking manoeuvre but leave speed control to drivers.

In the present study, an AS system was used. It controls the car's position in the lane by anticipating the changes in road curvature by means of video processing of road markings (Netto et al., 2003). Drivers can recover a manual control at any time by turning the steering wheel. Drivers were confronted to obstacles to skirt around under manual driving and when resuming manual control from automated driving was required. Assuming that the pool of attentional resources is fixed (Kahneman, 1973), drivers should have more resources available with AS than without, because AS is taking care of part of the steering task. In line with this idea AS device was shown to reduce mental workload (Stanton et al., 2001; Young & Stanton, 2002). However, mental workload reduction is not always related to an improvement of performances because it can lead to underload and associated performances degradation (Young, Brookhuis, Wickens, & Hancock, 2014). In addition, as described earlier, previous studies showed a decrease in driving performance with function delegation assistances (Hoc et al., 2006; Merat et al., 2014; Stanton et al., 2001). As a consequence AS was expected to deteriorate driving behaviours when resuming manual control was required to avoid obstacles.

A complementary objective was to analyse drivers' eyes positions during obstacle avoidance to investigate how drivers reorganize gaze behaviours when returning to manual control compared to unassisted driving. It has been demonstrated that the highest proportion of eye fixations during bend-taking is devoted to the area around the tangent point (Land & Lee, 1994), although the exact nature of the visual cues and gaze strategies used to steer the car is still highly debated (Lappi, 2014; Mars, 2008; Wilkie, Kountouriotis, Merat, & Wann, 2010). In a previous experiment, a redistribution of gaze orientation with respect to the tangent point was observed when driving with AS compared to unassisted driving (Mars & Navarro, 2012). When AS was active, the drivers increased the number of look-ahead fixations, i.e. far anticipatory glances that are not related to the current steering task, and reduced the number of guiding fixations in the vicinity of the tangent point. This has been interpreted as a change in the balance between cognitive and sensorimotor anticipatory control: As the need for visuomotor coordination was not as strong when using AS, the drivers may have disengaged to some extent from short term anticipation and looked for information further down the road. The present study extends this line of research by analysing the driver's gaze behaviour with AS when manual control must be resumed to avoid a collision.

2. Method

2.1. Participants

Eighteen certified drivers (2 women) with normal vision participated in this experiment. They had between 2 and 30 years of driving experience (mean 9 years ± 4.9) and reported an average mileage of 9185 km per year. None of them suffered for simulator sickness.

2.2. Materials

2.2.1. Driving simulation

The experiment was carried out on a fixed-base simulator (SIM^2, developed by IFSTTAR-MSIS on a FAROS platform) and a large screen viewed from a distance of 2 m provided a 62° width × 51° height of visual angle. The simulator cabin included a speedometer, an adjustable seat, a manual gearbox, force feedback steering wheel and pedals for brakes, accelerator, and clutch (Espié, Mohellebi, & Kheddar, 2003). The visual database used was a model of a real test-track located in Versailles (France) and was about 3.4 km long. This visual database was composed of a two-way main road with 14 bends of various length and curvature separated by 15 straight lines (Fig. 1).

2.2.2. Eye movement tracker

Participants' gaze positions were recorded at a sample rate of 50 Hz by means of the head-mounted IviewX system (Sensomotoric Instruments®), equipped with a magnetic tracker (Fastrack Polhemus®) to compensate for head movements. After the most accurate 13 points calibration procedure, gaze position accuracy was about 0.5°.

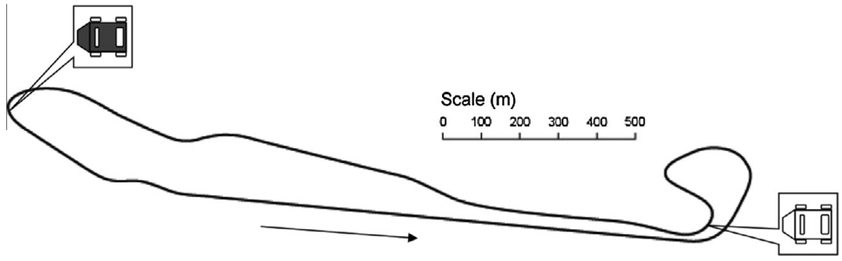

Fig. 1. Layout of the simulated two-way road. The arrow indicates the driving direction and the cars pictures the obstacles location (Obstacle 1 in black in a left bend and obstacle 2 in white in a right bend).

2.2.3. Automatic steering (AS)

The automatic steering device initially conceived on a real car (Chaib, Netto, & Mammar, 2004; Netto et al., 2003) was implemented into the driving simulator for the purpose of this experiment. Based on the vehicle position on its lane, a desired steering angle was continuously computed. An actuator (a direct current electric motor) acted on the steering column to follow this desired computed angle. The actuator was driven by a proportional controller that used the yaw angle error (angle between the vehicle heading the main axis of the road) and the vehicle lateral position relative to the lane centre.

Fig. 2 describes the working principle of the AS that allowed drivers to switch from automatic steering (AS on) to manual steering (AS off) and the reverse. Drivers were instructed to keep both hands on the steering wheel and to maintain a "10-to-2" standard position. This allowed drivers to have a continuous feedback from the AS actions on the steering wheel. Drivers were instructed to let AS steer as long as they judged its actions effective, but to disengage it whenever they felt it was necessary simply by turning the steering wheel. They were also told that if they chose to apply a torque on the steering wheel, lateral control would become entirely manual. The AS only reengaged after the car had remained in the driving lane for more than 2 s and the driver had stopped turning the steering wheel for the same amount of time. A green square was displayed at the bottom right of the visual scene to indicate the AS activation (AS on).

2.3. Procedure

Participants were instructed to drive along the road in their lane, to keep both hands on the steering wheel at any time, and to comply with speed limits. The assistance and its working principle were presented and participants were informed that they would have to drive with and without the assistance. The assistance was described as an automatic lane-keeping device effective under regular circumstances but unable to detect and avoid obstacles in that lane. It was specified that they would occasionally have to skirt around unannounced obstacles.

After two laps of familiarization with the track without assistance, the experimental trials proper began. A repeated measures design was used. Each participant drove for 7 laps with assistance (A) and 7 laps without (NA). Half of the participants began with assistance and the other half without. Obstacle skirting with assistance was programmed (but unknown from participants; see Fig. 1 for their location) during the 5th lap (obstacle 1) and the 7th lap (obstacle 2), and during the 2nd lap (obstacle 1) and the 4th lap (obstacle 2) without it. Obstacle 1 appeared at the exit of a left bend (curvature radius: 73 m). Obstacle 2 appeared in the middle of a right bend (radius: 80 m). Obstacle 1 was visible further in advance than obstacle 2, although the two appeared in relatively unpredictable way. Indeed when drivers faced obstacle 1, they only had about 2.9 s (±0.15) to detect and avoid the obstacle. A relatively longer 3.4 s (±0.15) period of time was available for obstacle 2. The obstacles were parked cars that straddled the driving lane and shoulder rather than covering the entire lane width. Because of that location on the road and the surprising appearance of the obstacles, all participants skirt around the obstacle by the left without braking to stop.

A random oncoming traffic (5–6 vehicles per km) was present during driving scenarios except during obstacle skirting. All in all, the experiment took about 100 min, including 25 min for eye tracker calibration.

2.4. Data analysis

Driving behaviour during obstacle skirting manoeuvres was assessed by means of the Time-To-Contact (TTC) with the obstacle and the analysis of the steering response (see Fig. 3 for an example). To verify that the vehicle speed was similar

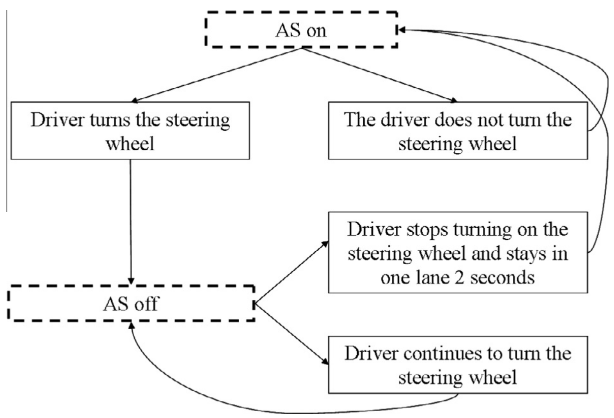

Fig. 2. The dotted boxes represent the Automatic Steering (AS) states. In the "AS on" state, automatic steering in engaged and takes care of the vehicle position on its driving lane. In the "AS off" state, automatic steering is disengaged and drivers manually steer the vehicle. The plain boxes represent all possible transitions between "AS on" and "AS off" states.

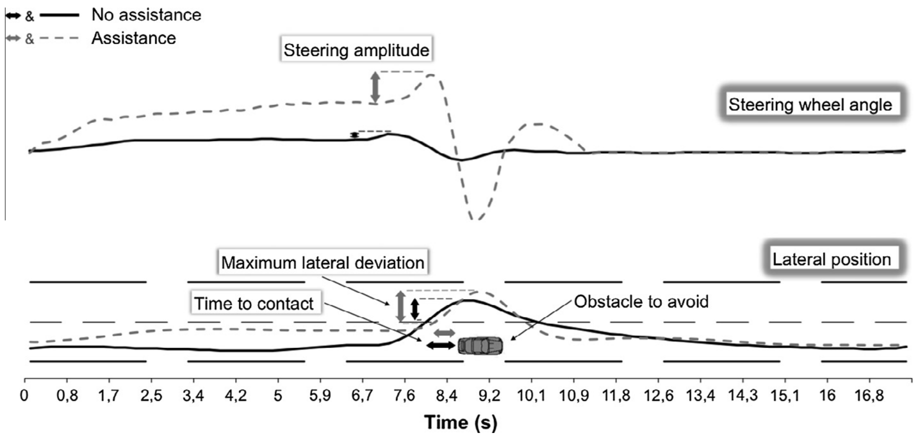

Fig. 3. A representative example of the obstacle avoidance manoeuvre and results recorded for both assistance and no assistance conditions.

in assisted and non-assisted conditions, the average vehicle speed when approaching the obstacles was analysed. The TTC was computed as the time remaining to reach the obstacle when the vehicle crossed the centre of the road. It is an indicator of the safety margin kept from the obstacle. The steering correction was decomposed in three measures. First, the steering amplitude indicates the size of the steering wheel correction adopted by drivers. Second, the steering wheel peak acceleration represents the strength of the steering. Third, the maximum lateral deviation in the left lane indicates the size of the lateral excursion related to the manoeuvre. For all those variables, a 2 × 2 repeated measure ANOVA with an assistance factor (No Assistance or Assistance) and an obstacle location factor (obstacle located on a left bend or a right bend) was used to assess driving behaviours.

Gaze behaviours during each obstacle-skirting manoeuvres (left and right bend obstacle) were analysed. Each recorded gaze position was plotted in a bi-dimensional space with the tangent point as its origin. The percentage of time spent by drivers looking in a region of 5° around the TP was computed in order to provide a global indicator of gaze positioning relative to the TP (Land & Lee, 1994). A 2 × 2 repeated measure ANOVA with an assistance factor (No Assistance or Assistance) and an obstacle location factor (obstacle located on a left bend or a right bend) was used to assess visual behaviours.

For a deeper analysis, the distribution of gaze positions was divided in proportion of gaze points in intervals of 1° of angular deviation from the TP. This procedure was carried out for both the vertical (Y-Axis) and horizontal (X-Axis) dimensions (see Fig. 4). All gaze points that deviated more than 15° from the TP in one direction or the other were regrouped in two extreme classes. Two-ways repeated measures analyses of variance (ANOVA) with assistance presence (assistance vs. no assistance) and the angular deviation from the tangent point (32 levels) as independent variable were performed on both vertical and horizontal gaze position data.

Bonferroni tests were used for post hoc analyses and statistical significance level was set at 0.05 for all analyses.

Finally, the first glance at the obstacle (i.e. time elapsed between obstacle appearance and first glance at the obstacle) and the total time drivers gazed at the obstacle were computed. A 2 × 2 repeated measure ANOVA with an assistance factor (No Assistance or Assistance) and an obstacle location factor (obstacle located on a left bend or a right bend) was used for statistics.

3. Results

3.1. Driving behaviours

3.1.1. Speed

No significant difference in speed was observed when negotiating the bends with or without assistance (NA-A: $d = 55.2–54.6 = 0.6$ kph; $F(1,17) = 0.14$; $p > .72$; $\eta^2 = 0.008$). The speed was higher in the bend with obstacle 1 compared to the bend with obstacle 2 (obstacle 1-obstacle 2: $d = 59.1–50.6 = 8.5$ kph; $F(1,17) = 20.92$; $p < .001$; $\eta^2 = 0.55$). No significant interaction was observed between assistance and obstacle location factors ($F(1,17) = 0.12$; $p > .74$; $\eta^2 = 0.007$).

3.1.2. TTC

The TTC was significantly reduced with the assistance by about 10% at the initiation of skirting manoeuvre compared to the no assistance condition ($d = 1084–823 = 261$ ms; $F(1,17) = 8.23$; $p < .01$; $\eta^2 = 0.33$; Fig. 5). Whatever the assistance condition, TTC was notably larger (about 20%) for the obstacle that was visible earlier (obstacle 1) compared to obstacle 2 ($d = 1126–781 = 345$ ms; $F(1,17) = 14.65$; $p < .002$; $\eta^2 = 0.46$). No significant interaction was observed between assistance and obstacle location factors ($F(1,17) = 0.65$; $p > .81$; $\eta^2 = 0.003$).

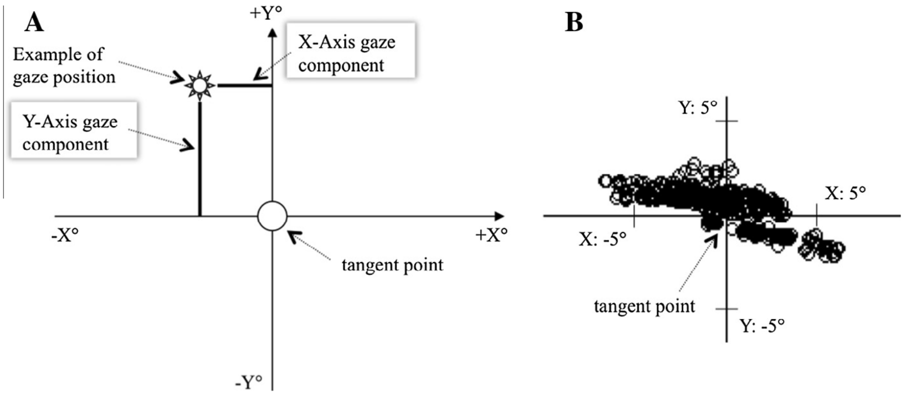

Fig. 4. (A) Example of a gaze position relative to the tangent point. (B) Example of cumulated gaze position relative to the tangent point (for a left bend in the no assistance condition and without obstacle).

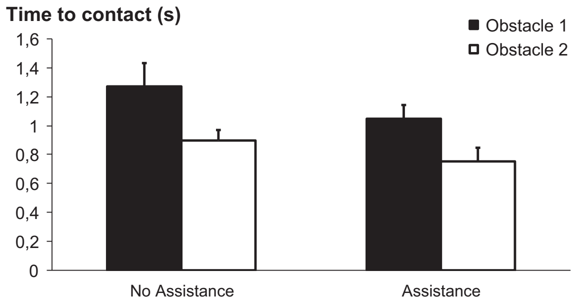

Fig. 5. Mean time to contact (TTC) in the No Assistance (NA) and Assistance (A) conditions for the two obstacles. Error bars represent one standard error.

3.1.3. Steering amplitude, steering wheel peak acceleration and maximum lateral deviation

The results for steering correction followed the same pattern. Steering amplitude, steering wheel peak acceleration, and maximum lateral deviation were significantly greater with assistance than without it. No obstacle location or interaction effects were revealed by the ANOVAs.

– About 33% more for steering amplitude ($d = 74.8–50.3 = 24.4°$; $F(1,17) = 19.26$; $p < .0001$; $\eta^2 = 0.53$).
– About 50% more for steering wheel peak acceleration ($d = 24.0–14.4 = 9.6°/s^2$; $F(1,17) = 22.69$; $p < .0001$; $\eta^2 = 0.57$).
– About 40% more for maximum lateral deviation ($d = 2.96–2.06 = 0.90$ m; $F(1,17) = 14.89$; $p < .002$; $\eta^2 = 0.47$).

3.2. Gaze behaviours

3.2.1. Percentage of time spent looking around the tangent point (TP)

The analysis of variance showed a main effect of the assistance factor on the time spent looking in the tangent point area ($F(1,17) = 25.07$; $p < .0001$; $\eta^2 = 0.60$). Drivers spent significantly less time looking around the tangent point (±5°) with assistance (35.4% of the time) compared to the no assistance condition (61.9% of the time).

No main effect of the obstacle location (in a left or a right bend) and no interaction between the assistance and the obstacle location was found ($F(1,17) = 0.63$; $p > .44$; $\eta^2 = 0.04$ and $F(1,17) = 3.59$; $p > .08$; $\eta^2 = 0.17$ respectively; see Fig. 6).

Fig. 7 represents the distribution of gaze positions as a function of horizontal and vertical angular deviation from the tangent point for both obstacle 1 and 2. The analysis of the interaction between assistance condition (NA, A) and angular deviation from the tangent point (from <−15 to >15) offers a more detailed picture of drivers' gaze behaviours.

3.2.2. Obstacle 1 (left bend)

3.2.2.1. Horizontal analysis. A significant interaction was found between the assistance condition and the horizontal angular deviation from the tangent point ($F(31,512) = 3.05$; $p < .0001$; $\eta^2 = 0.16$; Fig. 7 bottom left). Post-hoc analysis indicated a significant difference between the no assistance and assistance conditions at ten different angular deviations ($p < 0.05$). With assistance, fewer gaze positions between −4° and +1° from the tangent point were recorder than without assistance. With assistance gaze positions were deviated to the left (between −7° and −14°) compared to the no assistance condition.

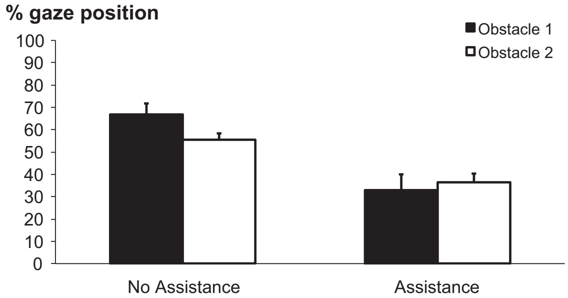

Fig. 6. Mean percentage of gaze position spend looking around the tangent point (5°) in the No Assistance (NA) and Assistance (A) conditions for the two obstacles. Error bars represent one standard error.

3.2.2.2. Vertical analysis. A significant interaction was found between the assistance condition and the vertical angular deviation from the tangent point ($F(31,512) = 5.17$; $p < .0001$; $\eta^2 = 0.24$; Fig. 7 bottom right). Post-hoc analysis indicated a significant difference between the no assistance and assistance conditions at eight different angular deviations ($p < 0.05$). With assistance, fewer gaze positions between +1° and +3° from the tangent point were recorded than without assistance. Additionally, drivers looked further ahead with assistance than without, this was significant at four angular deviations over 7° upward from the tangent point.

3.2.3. Obstacle 2 (right bend)

3.2.3.1. Horizontal analysis. A significant interaction was found between the assistance condition and the horizontal angular deviation from the tangent point ($F(31,512) = 3.54$; $p < .0001$; $\eta^2 = 0.18$; Fig. 7 top left). Post-hoc analysis indicated a significant difference between the no assistance and assistance conditions at six different angular deviations ($p < 0.05$). Significantly more gaze positions were recorded at the two extreme angular positions (>15° and <−15°) with assistance compared to no assistance. Conversely, fewer gaze positions between −5° and 2° from the tangent point were recorded with assistance than without assistance. Globally, gaze positions were deviated to the right with assistance.

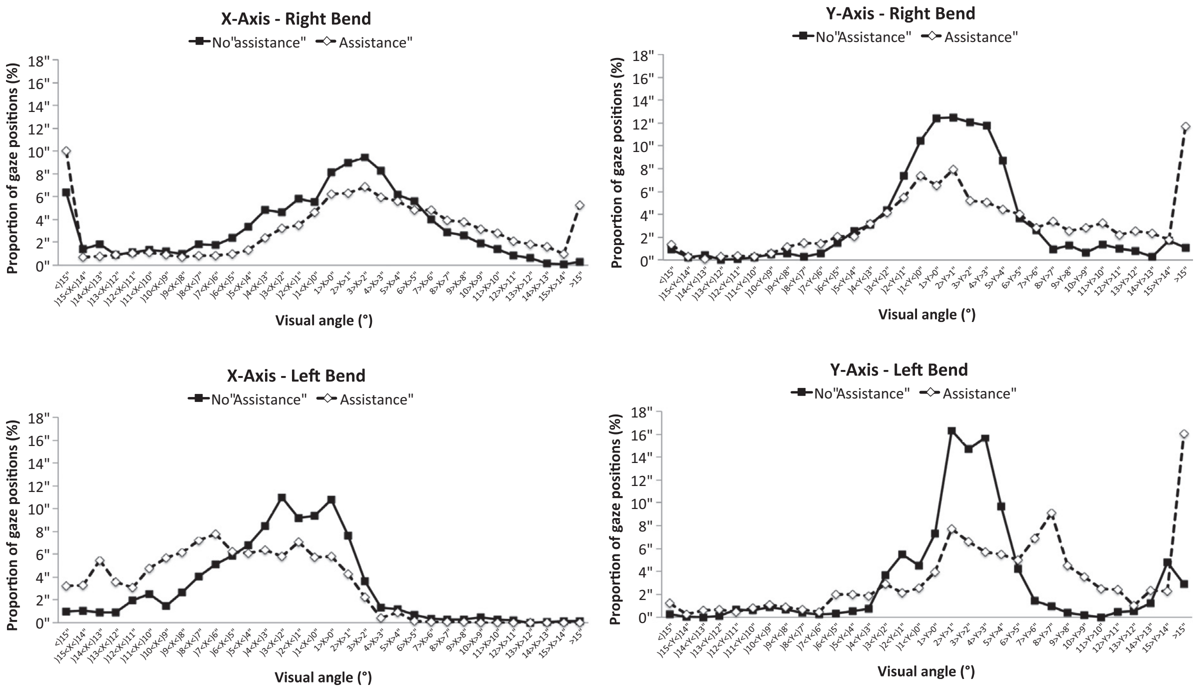

Fig. 7. Distribution of gaze positions as a function of horizontal and vertical angular deviation from the tangent point. The top part of the figure represents the right bend and the bottom part the left bend. The left part of the figure represents horizontal angular deviation and the right part vertical angular deviation. A positive value on the X-axis represents a gaze deviation to the right of the tangent point and a positive value on the Y-axis represents a gaze deviation beyond the tangent point. Asterisks indicate significant differences between No Assistance and Assistance conditions.

3.2.3.2. Vertical analysis. A significant interaction was found between the assistance condition and the vertical angular deviation from the tangent point ($F(31,512) = 7$; $p < .0001$; $\eta^2 = 0.30$; Fig. 7 top right). Post-hoc analysis indicated a significant difference between the no assistance and assistance conditions at nine different angular deviations ($p < 0.05$). With assistance fewer gaze positions between $-1°$ and $+4°$ from the tangent point were recorder than without assistance. Additionally, drivers looked further ahead with assistance than without, the difference was significant at three angular deviations over 7° upward from the tangent point.

3.2.4. First glance at obstacle and total time drivers gazed at obstacle

3.2.4.1. First glance at obstacle. The ANOVA did not reveal any significant difference for assistance (No Assistance or Assistance; $d = 508–480 = 28$ ms; $F(1,17) = 0.75$; $p > .39$; $\eta^2 = 0.04$), obstacle location (obstacle located on a left bend or a right bend; $d = 467–519 = -52$ ms; $F(1,17) = 1.13$; $p > .30$; $\eta^2 = 0.06$) and the interaction between those two factors ($F(1,17) = 0.66$; $p > .42$; $\eta^2 = 0.04$).

3.2.4.2. Total time drivers gazed at obstacles. No significant difference between no assistance and assistance and no interaction between assistance presence or not and obstacle location were recorded regarding the time obstacles were gazed (respectively $d = 1.06–1.21 = -0.15$ s; $F(1,17) = 1.24$; $p > .39$; $\eta^2 = 0.08$ and $F(1,17) = 0.00$; $p > .96$; $\eta^2 = 0.00$). But drivers spent more time looking at obstacle 2 than at obstacle 1 ($d = 1.363–0.908 = 0.455$ s; $F(1,17) = 14.08$; $p < .002$; $\eta^2 = 0.45$).

4. Discussion

Data showed that driving with automatic steering resulted in difficulties in returning to manual control during obstacle avoidance. The analysis of gaze behaviours also highlighted a modification of visual exploration patterns when lateral control was delegated to automation. Drivers spent less time looking at the area of the tangent point, a part of the visual scene that is known to be crucial for steering control, and favoured looking further ahead for visual exploration. Those visual changes tend to indicate a transfer from visual scanning devoted to steering control to a visual scanning devoted to anticipate incoming events.

It has been clearly established that, when drivers skirted around an obstacle, they experienced difficulties in moving from automatic steering back to manual control. This result directly reinforces previous observations by Hoc et al. (2006). Here, several variables allowed for a detailed characterization of these difficulties. In the assisted condition, skirting manoeuvres were initiated 250 ms later on average, which means that the drivers changed lanes about 4 m closer to the obstacle at the observed speed. The size and the vivacity of the steering wheel corrections also increased, which resulted in exaggerated deviations within the left lane. In terms of maximum lateral deviation, if left road departure is considered as the largest lateral deviation (100%), the drivers' average maximum lateral deviation was 84% with automatic steering, instead of 59% without. The experiment scenarios were not designed to yield crashes and none was observed: the participants always succeeded in avoiding collisions. However, in more critical situations, late and rough steering responses may have consequences in terms of safety, such as road departure or collision with oncoming traffic.

In the current experiment, the drivers were relieved from the steering task by the automation. As a consequence, they disengaged from that task, which resulted in difficulties in resuming manual control. The disengagement of the human from a task he used to perform before automation replaced him has been described earlier (Billings, Lauber, Funkhouser, Lyman, & Huff, 1976; Moray, 2003; Parasuraman & Manzey, 2010; Wiener, 1981) and more recently in highly automated driving (Louw, Kountouriotis, Carsten, & Merat, 2015). This disengagement from the task is a form of negative behavioural adaptation, a phenomenon that covers every (positive or negative) unexpected change in behaviour brought about by automation (OECD, 1990; Rudin-Brown & Parker, 2004). The disengagement from the steering task might led to negative behavioural adaptation though several ways (a) drivers are out of the control loop of vehicle steering, their awareness of the situation and the assistance states might be reduced (Kaber & Endsley, 1997), (b) drivers might rely too much on automation and become complacent (Parasuraman & Manzey, 2010), (c) drivers might face suboptimal mental workload and face underload (Young & Stanton, 2002; Young et al., 2014). To those three manifestations of disengagement, in case of an obstacle to avoid drivers had to make the decision to return and then perform the steering adjustments. Without automation, they must only perform the steering. This could also contribute to explain the drop in skirting manoeuvres performances with automatic steering.

Eye movement analyses confirmed that the introduction of AS led to a modification of gaze strategies. This confirmed previous observations made during bend taking without obstacles. More look-ahead fixations were also observed (Mars & Navarro, 2012). However, Mars and Navarro (2012) only reported a moderate (about 5%) shift from short term guiding fixations to look-ahead fixations. Here, during obstacle skirting, the changes in visual strategies with AS appear to be much more important. A detailed analysis of horizontal and vertical gaze positions showed that, with AS, drivers looked further ahead with gaze positions being more spread out horizontally towards the inside of the bend and vertically towards the horizon. In more details, drivers spent more than 10% more time (NA: 56.4%, A: 66.8%) looking to the right of the tangent point in the right bend and about 15% more time (NA: 71.1%, A: 86%) looking to the left of the tangent point in the left bend. With assistance, more glances were also directed to the far distance (7° or more beyond the tangent point). More precisely, drivers spent more than 24% more time (NA: 12%, A: 36.1%) looking higher in the right bend with AS than without AS. The difference reached 36% (NA: 14%, A: 50.2%) in the left bend.

These observations not only confirms drivers' disengagement from the steering task reported previously, it also indicates that drivers withdraw is not only affecting vehicular control but also automatic visual scanning of the driving scene. Indeed the tangent point region is the location of the visual scene where drivers naturally look to steer the car. It can be hypothesized that automatic steering diminish the need for eye-steering coordination resulting in a visual disengagement from the tangent point area. Gaze behaviour changes may be interpreted as a global change in the driver's activity. With assistance, less attention was allocated to the tangent point area where the visual information required to steer the car is present and more attention was given to side and far distance information. This increase in "look-ahead fixations" may be view as an attempt to anticipate future road curvature or identify future hazards, i.e. to plan future actions in advance (Mennie, Hayhoe, & Sullivan, 2007). Changes in gaze strategies would then reflect the driver's role switching from steering the car to monitoring in advance potential hazards. However, drivers were not able to see the obstacle far in advance, only about 3 s were available to detect and avoid the obstacle. In that particular case, the shift to an anticipative behaviour with automation did not translate in a significant reduction of first glance at obstacle nor at more time gazed at the obstacle. Nevertheless assistance induced a difficulty to adequately steer the vehicle around the obstacles. This suggests that drivers of autonomous vehicles are, at least, not disadvantaged at anticipating hazards. If obstacles would appear far in advance, they might even become better at anticipating hazards because they do not need to process visual information for steering control. But it may be at the cost of a loss of capacity to react to a sudden unpredictable event. Further investigations are required to shed light on this important question in the context of the development of highly automated vehicles.

5. Conclusion

In summary, this experiment showed drivers' difficulty in returning to manual control with automated steering when the driver was in a situation that was outside the machine's validity domain (avoid an obstacle). Eye movements' analysis revealed a reduction in the time spent at looking in the tangent point area, which reflect a modification of eye-steering coordination. AS was associated with more look-ahead fixations and more glances to side information of the roadway were recorded. Changes in visual scanning were irrelevant for steering control in case drivers had to return to manual control in case of surprising obstacles appearance. This study also contributes to the development of a future highly automated car. As long as the automation is imperfect and the driver presence required for the vehicle control, it is absolutely essential to understand human-machine cooperation so as to anticipate possible counterproductive automation effects. Our results showed that resuming manual control is not only a problem of action performance but also come with a deeper reorganisation of drivers' activity, as observed through changes in visual strategies. Results also question assistances that replace drivers for part of their usual activity but sometimes require drivers' intervention. From the human perspective this seems to be a very challenging cooperation situation.

Acknowledgments

This study was performed with the financial support of ANR (PREVENSOR Program) and the technical support of IFSTTAR-MSIS, IFSTTAR-LIVIC, and Robert Boisliveau at CNRS-IRCCyN.

References

Abbink, D. A., Mulder, M., & Boer, E. R. (2012). Haptic shared control: Smoothly shifting control authority? *Cognition Technology & Work, 14*(1), 19–28. http://dx.doi.org/10.1007/s10111-011-0192-5.

Billings, C. E., Lauber, J. K., Funkhouser, H., Lyman, E. G., & Huff, E. M. (1976). *NASA aviation safety reporting system* Tech. Rep. TM-X-3445. Moffett Field, CA: NASA Ames Research Center.

Carsten, O., Lai, F. C. H., Barnard, Y., Jamson, A. H., & Merat, N. (2012). Control task substitution in semiautomated driving: Does it matter what aspects are automated? *Human Factors: The Journal of the Human Factors and Ergonomics Society, 54*(5), 747–761. http://dx.doi.org/10.1177/0018720812460246.

Chaib, S., Netto, M. S., & Mammar, S. (2004). $H\infty$, adaptive, PID and fuzzy control: A comparison of controllers for vehicle lane keeping. In *IEEE intelligent vehicles symposium. Parma, Italy* (pp. 139–144).

de Winter, J. C. F., Happee, R., Martens, M. H., & Stanton, N. A. (2014). Effects of adaptive cruise control and highly automated driving on workload and situation awareness: A review of the empirical evidence. *Transportation Research Part F: Traffic Psychology and Behaviour, 27*, 196–217. http://dx.doi.org/10.1016/j.trf.2014.06.016.

Deroo, M., Hoc, J.-M., & Mars, F. (2012). Influence of risk expectation on haptically cued corrective manoeuvres during near lane departure. *Ergonomics, 55*(4), 465–475. http://dx.doi.org/10.1080/00140139.2011.647094.

Deroo, M., Hoc, J.-M., & Mars, F. (2013). Effect of strength and direction of haptic cueing on steering control during near lane departure. *Transportation Research Part F-Traffic Psychology and Behaviour, 16*, 92–103. http://dx.doi.org/10.1016/j.trf.2012.08.015.

Espié, S., Mohellebi, H., & Kheddar, A. (2003). A high performance/low-cost mini driving simulator alternative for human factor studies. In *Driving Simulation Conference* (pp. 10).

Hoc, J.-M., Mars, F., Milleville-Pennel, I., Jolly, É., Netto, M., & Blosseville, J.-M. (2006). Human-machine cooperation in car driving for lateral safety: Delegation and mutual control. *Le Travail Humain, 69*(2), 153–182.

Hoc, J.-M., Young, M. S., & Blosseville, J.-M. (2009). Cooperation between drivers and automation: Implications for safety. *Theoretical Issues in Ergonomics Science, 10*(2), 135–160.

Kaber, D. B., & Endsley, M. R. (1997). Out-of-the-loop performance problems and the use of intermediate levels of automation for improved control system functioning and safety. *Process Safety Progress, 16*(3), 126–131.

Kahneman, D. (1973). *Attention and effort*. New Jersey, USA: Prentice Hall.

Land, M. F., & Lee, D. N. (1994). Where do we look when we steer. *Nature, 369*(6483), 742–744.
Lappi, O. (2014). Future path and tangent point models in the visual control of locomotion in curve driving. *Journal of Vision, 14*(12), 1–22. http://dx.doi.org/10.1167/14.12.21.
Larsson, A. F. L., Kircher, K., & Andersson Hultgren, J. (2014). Learning from experience: Familiarity with ACC and responding to a cut-in situation in automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 27*, 229–237. http://dx.doi.org/10.1016/j.trf.2014.05.008.
Louw, T., Kountouriotis, G., Carsten, O., & Merat, N. (2015). Driver distraction during vehicle automation : How does driver engagement affect resumption of control ? In *4th international driver distraction and inattention conference, Sydney, New South Wales*. http://dx.doi.org/10.13140/RG.2.1.2017.0089.
Markoff, J. (2010). Google cars drive themselves, in traffic. *New York Times*. Available from http://www.nytimes.com/2010/10/10/science/10google.html?scp=1&sq=look%20officer,%20no%20hands&st=cse.
Mars, F. (2008). Driving around bends with manipulated eye-steering coordination. *Journal of Vision, 8*(11), 1–11. http://dx.doi.org/10.1167/8.11.10.
Mars, F., Deroo, M., & Charron, C. (2014). Driver adaptation to haptic shared control of the steering wheel. In *Proceedings of the 2014 IEEE international conference on systems, man, and cybernetics. San Diego* (pp. 1524–1528).
Mars, F., Deroo, M., & Hoc, J.-M. (2014). Analysis of human-machine cooperation when driving with different degrees of haptic shared control. *IEEE Transactions on Haptics, 7*(3), 324–333. http://dx.doi.org/10.1109/TOH.2013.2295095.
Mars, F., & Navarro, J. (2012). Where we look when we drive with or without active steering wheel control. *PLoS ONE, 7*(8), e43858. http://dx.doi.org/10.1371/journal.pone.0043858.
Mennie, N., Hayhoe, M., & Sullivan, B. (2007). Look-ahead fixations: Anticipatory eye movements in natural tasks. *Experimental Brain Research, 179*(3), 427–442.
Merat, N., Jamson, A. H., Lai, F. C. H., & Carsten, O. (2012). Highly automated driving, secondary task performance, and driver state. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 54*(5), 762–771. http://dx.doi.org/10.1177/0018720812442087.
Merat, N., Jamson, A. H., Lai, F. C. H., Daly, M., & Carsten, O. M. J. (2014). Transition to manual: Driver behaviour when resuming control from a highly automated vehicle. *Transportation Research Part F: Traffic Psychology and Behaviour, 27*, 274–282. http://dx.doi.org/10.1016/j.trf.2014.09.005.
Merat, N., & Lee, J. D. (2012). Preface to the special section on human factors and automation in vehicles: Designing highly automated vehicles with the driver in mind. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 54*(5), 681–686. http://dx.doi.org/10.1177/0018720812461374.
Moray, N. (2003). Monitoring, complacency, scepticism and eutactic behaviour. *International Journal of Industrial Ergonomics, 31*(3), 175–178.
Mulder, M., Abbink, D. A., & Boer, E. R. (2012). Sharing control with haptics: Seamless driver support from manual to automatic control. *Human Factors, 54*(5), 786–798.
Najm, W. G., Smith, J. D., & Yanagisawa, M. (2007). *Pre-crash scenario typology for crash avoidance research* (Tech. Rep. DOT-HS-810 767). United States: National Highway Transportation Safety Administration Research.
Navarro, J., Mars, F., Forzy, J.-F., El-Jaafari, M., & Hoc, J.-M. (2010). Objective and subjective evaluation of motor priming and warning systems applied to lateral control assistance. *Accident Analysis and Prevention, 42*(3), 904–912. http://dx.doi.org/10.1016/j.aap.2009.07.008.
Navarro, J., Mars, F., & Hoc, J.-M. (2007). Lateral control assistance for car drivers: A comparison of motor priming and warning systems. *Human Factors, 49*(5), 950–960. http://dx.doi.org/10.1518/001872007X230280.
Navarro, J., Mars, F., & Young, M. S. (2011). Lateral control assistance in car driving: Classification, review and future prospects. *IET Intelligent Transport Systems, 5*(3), 207. http://dx.doi.org/10.1049/iet-its.2010.0087.
Netto, M., Labayrade, R., Ieng, S. S., Lusetti, B., Blosseville, J. M., & Mammar, S. (2003). Different modes on shared lateral control. In *10th ITS World Congress. Madrid, Spain.* .
NHTSA (2008). *National motor vehicle crash causation survey*.
OECD (1990). *Behavioural adaptations to changes in the road transport system. Paris*.
Parasuraman, R., & Manzey, D. H. (2010). Complacency and bias in human use of automation: An attentional integration. *Human Factors, 52*(3), 381–410. http://dx.doi.org/10.1177/0018720810376055.
Rudin-Brown, C. M., & Parker, H. A. (2004). Behavioural adaptation to adaptive cruise control (ACC): Implications for preventive strategies. *Transportation Research Part F: Traffic Psychology and Behaviour, 7*(2), 59–76.
Stanton, N. A., Young, M. S., Walker, G. H., Turner, H., & Randle, S. (2001). Automating the driver's control tasks. *International Journal of Cognitive Ergonomics, 5*(3), 221–236. http://dx.doi.org/10.1207/S15327566IJCE0503_5.
Strand, N., Nilsson, J., Karlsson, I. C. M., & Nilsson, L. (2014). Semi-automated versus highly automated driving in critical situations caused by automation failures. *Transportation Research Part F: Traffic Psychology and Behaviour, 27*, 218–228. http://dx.doi.org/10.1016/j.trf.2014.04.005.
Thrun, S., Montemerlo, M., Dahlkamp, H., Stavens, D., Aron, A., Diebel, J., ... Hoffmann, G. (2007). Stanley: The robot that won the DARPA Grand Challenge. In *The 2005 DARPA Grand Challenge* (pp. 1–43). Springer.
van Paassen, M. M. (2010). Heidegger versus Carthesian Dualism or where is my hammer? In *2010 IEEE international conference on systems, man and cybernetics* (pp. 1684–1688). IEEE. http://dx.doi.org/10.1109/ICSMC.2010.5642318.
Volvo Cars. (2013). Volvo Car Group initiates world unique Swedish pilot project with self-driving cars on public roads.
Wiener, E. L. (1981). Complacency: Is the term useful for air safety. In I. Flight Safety Foundation (Ed.). *Proceedings of the 26th corporate aviation safety seminar. Denver, CO* (Vol. 117, pp. 116–125). .
Wilkie, R. M., Kountouriotis, G. K., Merat, N., & Wann, J. P. (2010). Using vision to control locomotion: Looking where you want to go. *Experimental Brain Research, 204*(4), 539–547. http://dx.doi.org/10.1007/s00221-010-2321-4.
Young, M. S., Brookhuis, K. A., Wickens, C. D., & Hancock, P. A. (2014). State of science: Mental workload in ergonomics. *Ergonomics* (January 2015), 37–41. http://dx.doi.org/10.1080/00140139.2014.956151.
Young, M. S., & Stanton, N. A. (2002). Malleable attentional resources theory: A new explanation for the effects of mental underload on performance. *Human Factors, 44*(3), 365–375. http://dx.doi.org/10.1518/0018720024497709.
Young, M. S., Stanton, N. A., & Harris, D. (2007). Driving automation: Learning from aviation about design philosophies. *International Journal of Vehicle Design, 45*(3), 323–338.