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ARTICLE



Visual and steering behaviours during lane departures: a longitudinal study of interactions between lane departure warning system, driving task and driving experience

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ABSTRACT

Lane Departure Warning Systems (LDWS) generate a warning in case of imminent lane departure. LDWS have proven to be effective and associated human-machine cooperation modelled. In this study, LDWS acceptance and its impact on visual and steering behaviour have been investigated over 6 weeks for novice and experienced drivers. Unprovoked lane departures were analysed along three driving tasks gradually more demanding. These observations were compared to a baseline condition without automation. The number of lane departures and their duration were dramatically reduced by LDWS, and a narrower visual spread of search during lane departure events was recorded. The findings confirmed LDWS effectiveness and suggested that these benefits are supported by visuo-attentional guidance. No specific influence of driving experience on LDWS was found, suggesting that similar cognitive processes are engaged with or without driving experience. Drivers' acceptance of LDWS lowered after automation use, but LDWS effectiveness remained stable during prolonged use.

Practitioner summary: Lane Departure Warning Systems (LDWS) have been designed to prevent lane departure crashes. Here, LDWS assessment over a 6-week period showed a major drop in the number of lane departure events increasing over time. LDWS effectiveness is supported by the guidance of drivers' visual attention during lane departure events.

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Human-machine cooperation; warning; unprovoked lane departure; visual behaviours; steering behaviours; acceptance; car driving

1. Introduction

Technology achievements are key in our societies including in the automotive domain (Navarro 2019a, 2019b). As a matter of fact, our species has a long-lasting relationship with our so-called tools. Those tools, understood as all forms of artefacts from the simplest stick to the most advanced technology, not only assist or replace humans in a variety of situations but also contribute to shaping us (Navarro and Hancock 2023). It is therefore of major interest to better describe and characterise human-machine relationships.

Warnings have been used to assist humans in a variety of tasks, including driving, for several decades (e.g. Parasuraman, Hancock, and Olofinboba 1997). They consist of sensory alerts delivered to the user whenever a set of conditions, including imminent danger, has been met. Car driving is a complex task that

could be decomposed into a large number of sub-tasks (McKnight and Adams 1970a, 1970b). Among those tasks, vehicle control is directly linked to steering and can be divided into lateral control (i.e. adjusting the position of the vehicle in the driving lane) and longitudinal control (i.e. adjusting vehicle speed and leading headway) (Stanton et al. 2001). Both longitudinal and lateral control can be assisted with warning devices referred to as forward collision warning systems and Lane Departure Warning Systems (LDWS) respectively.

Regarding lateral control, LDWS has been investigated under a variety of designs and situations (see Beruscha, Augsburg, and Manstetten 2011; Navarro 2017; Navarro, Mars, and Young 2011 for reviews). In brief, LDWS generates a warning when the lateral position of the vehicle is judged as unsafe by automation. LDWS have been designed to enhance safety by

reducing the number of lane departures. Such automation could be considered as a technological extension of the rumble strip located along the driving lane boundaries. LDWS have proven to be effective in reducing the Steering Reaction Times (SRT) (e.g. Kozak et al. 2006; Navarro, Mars, and Hoc 2007; Rossmeier, Grabsch, and Rimini-Döring 2005) and the number, magnitude, and Duration of Lateral Excursions (DLE) of lane departures (Deroo, Hoc, and Mars 2012, 2013; Hoc et al. 2006; Navarro et al. 2010, 2016, 2017; Navarro, Mars, and Hoc 2007; Rimini-Döring et al. 2005; Suzuki and Jansson 2003). Although incorrect warnings (i.e. missed warnings, false warnings or a combination of both) could mitigate the benefits of LDWS, the negative impact appeared to be restricted to the lane departure considered and/or the subsequent lane departure (Navarro, Deniel, et al. 2019; Navarro et al. 2016, 2017).

When an LDWS is available, both the driver and the automation monitor the lateral position of the vehicle in its lane. In terms of human-machine cooperation, this particular form of automation is referred to as a mutual control mode of cooperation (Hoc 2000, 2001; Hoc, Young, and Blosseville 2009; Navarro, Mars, and Young 2011). The driver can act on the vehicle position by turning the steering wheel at all times, while the LDWS delivers a warning when the vehicle has reached the driving lane borders. Based on the available literature, a human-machine cooperation model describing human-machine interferences while using a LDWS has been proposed (Navarro 2017). In this model, human information processing is described to be under the influence of the driving situation, LDWS characteristics (e.g. sensory modality used, warning onset, duration), and the driver's characteristics. The human information processing itself is composed of (i) an attention and perception module and (ii) a situation diagnosis and control module. As a result of the information processing stage, drivers perform steering actions and adjust the mental representations of themselves, the LDWS, and the interaction of both. LDWS acceptance and use rely on those mental representations and actual steering performances.

When the vehicle is in a safe position in the driving lane, no warning is delivered, and the drivers keep on monitoring the vehicle position and steering accordingly. If despite these regulations, the vehicle reaches a border of the driving lane, a warning is delivered. Once delivered, the warning is expected to directly impact on the two modules of human information processing: (i) on the attention and perception module, by interrupting the task the driver was currently

involved in, pre-activating a motor response and potentially directing the driver's attention spatially to relevant locations of the driving scene; (ii) on the situation diagnosis and control module, the drivers are then expected to perform a diagnosis of the situation and control the situation mainly by applying rules-based behaviours (as defined by Rasmussen 1983, 1986). Other levels of cognitive control, namely knowledge-, skills- and emotion-based behaviours may also be engaged (Lehto 2000; Lehto and Foley 1991; Lehto and Papastavrou 1993).

In the reported experiment, if the LDWS characteristics were fixed (i.e. the same auditory warning was used to warn all the lane departure events) both the human characteristics and driving environment have been manipulated experimentally. These two elements are considered able to influence the information processing stage during warned lane departures (Navarro 2017).

Regarding human characteristics, the driving expertise has been manipulated with the inclusion of licenced drivers with at least four years of driving experience and unlicensed novice drivers. Expertise, understood as an assemblage of knowledge and skills gradually gained through formation and practice (Anderson 2000; Ericsson, Krampe, and Tesch-Römer 1993), is considered as a major component of performance in real-life activities. Based on an extensive literature review, experts are described as: (i) excelling in their own domain but are unlikely to excel in other domains, (ii) have a pattern-oriented perception rather than a fragmented perception, (iii) quickly solve problems with little error, (iv) have superior memory skills, (v) build their mental representations at a high level of abstraction, (vi) spend a lot of time analysing problems qualitatively and (vii) have developed strong self-monitoring strategies (Glaser and Chi 1988). If automation was observed to benefit experts and novices in a similar manner, when given the opportunity to choose among different automation solutions and contrary to novices, experts favour automation that enhances their expertise while novices used all automation solutions available in a similar proportion (Navarro, Allali, et al. 2021). Here, we aimed at investigating how driving expertise could interfere with LDWS use. As mentioned above, the focus was set on two levels of driving expertise through the constitution of two groups of participants. A group of unlicensed drivers, with no formation and no practice, hereafter referred as 'novice drivers', and a group of 'experienced drivers' with a driving expertise relying upon (i) a formation consisting in a driving training

course of at least 20 h (French legal framework) with a driver instructor, (ii) driving skills certified by the success at the French driving licence tests, including a real driving test assessed by an independent driving examiner and (iii) several years of driving practice, in detail only licenced drivers with at least four years of driving experience were included. The term 'experienced drivers' was favoured over 'expert drivers' to distinguish the driving expertise targeted here from professional driving expertise associated with racing drivers or professional drivers.

Regarding the driving environment, no specific methodology was used to generate lane departure events. Participants were simply asked to drive in a simulated environment composed of three different driving tasks (i.e. driving on a highway, driving on a bendy road, and driving to follow a vehicle). Road type (highway versus urban) is known to impact reaction time and accuracy at a secondary task (Baldwin, Freeman, and Coyne 2004). Workload and visual behaviour were also reported to be correlated with the complexity of road type (Yao et al. 2023). The three driving tasks used here were thus expected to be gradually more demanding from the highway task, then the bendy road task, and finally the car-following task. In our experiment, driving on a highway was a less demanding task as only a few speed and lateral adjustments were needed. Driving along a bendy road was more demanding as lateral control was continuously required to keep a correct lane position within the bends, while the speed control was unconstrained. The car-following situation was the most demanding task because it required participants to steer the vehicle to adjust the lateral position to the road curvatures, but also to adapt the vehicle speed to the continuously changing speed of the leading vehicle resulting in a highly demanding task.

Besides, an important issue tackled by the current work is the investigation of LDWS impact on performances and drivers' behaviour over an extended period of several weeks. Studying human-machine cooperation over time is key to understand not only the immediate effect of automation use but also potential longer-term effects. It is assumed that a slow component of automation use takes place only after prolonged exposure to the considered automation (Navarro and Hancock 2023).

The reported work was built on a mixed experimental design using a well-controlled driving simulated environment. No lane departure induction (such as secondary task, by distraction, visual occlusion, or induced drowsiness for instance) was used, and

natural lane departure events were considered. Participants were invited to drive manually or with LDWS in a simulated environment three times a week for six consecutive weeks. The first drive of each week was the same drive of interest reported here and was composed of three different driving tasks (i.e. highway, bendy road, and car-following). The two remaining drives were additional training sessions. During the drive of interest, visual and steering behaviours were recorded. In driving research, eye-movements measures are of particular interest to qualify visual attention regarding the visuo-motor driving task (Crundall and Underwood 2011), including considering the influence of driving experience (see Robbins and Chapman 2019 for a review). In the recent years much attention was paid to the visual behaviours engaged during transition of control between automated and manual driving, revealing an increased gaze dispersion under automated driving (see Deniel and Navarro 2023 for a review). Highly automated driving was also reported to impact the visual sequences engaged by drivers (Navarro 2019a; Navarro, Lappi, et al. 2021). But eye-movements are also known to be coordinated with steering under manual and automated driving (Navarro et al. 2020).

Steering behaviours were investigated through the number of lane departure events, the lane departure frequency, as well as the duration of lateral excursions, and the steering reaction times during the lane departure episodes. Visual behaviours were analysed in terms of spread of search in both horizontal and vertical components and in terms of fixation durations, as an indicator of the time taken to embrace fixated elements. Before the first drive and after the last drive, participants that used an LDWS (i.e. half of them) were also asked to fill in an acceptance questionnaire (Venkatesh et al. 2003).

With the LDWS available, the number and frequency of lane departures as well as the duration of lateral excursions were expected to decrease compared to unassisted driving. Due to poorer steering control, this decrease should be more drastic for novice drivers than for experienced drivers. Such benefits were hypothesised to be backed up by a reduction of the visual spread of search and faster visual processing of the driving scene in case of a lane departure event, thanks to the visual attentional guidance associated with the LDWS. The impact of warnings was expected to be modulated according to the driving tasks considered. Warnings should provide the highest benefits for the most demanding driving situations. According to the cognitive load hypothesis this effect should be

more pronounced for novice drivers as they cannot rely on automatic performances (Engström et al. 2017). LDWS influence was also projected to strengthen over time, resulting in more benefits after several weeks than after initial use. Finally, LDWS acceptance was hypothesised to be higher for novices than experienced drivers.

2. Method

2.1. Participants

Forty volunteers took part in this experiment. To be included, volunteers should be aged between 22 and 45 years old, have normal or corrected-to-normal vision and either hold a driving licence for at least 4 years or do not have a driving licence. Twenty participants were assigned to the experiment in the Assisted (A) condition and the other 20 to the Manual (M) condition.

In the A condition, ten were licenced drivers, hereafter referred to as experienced drivers [mean age: 23.3 years (± 2.1); mean driving experience: 5.1 years (± 2.0); mean kilometres driven per year declared: 9098 km (± 7476); mean number of post-baccalaureate years: 3.1 years, 6 females] and ten non-licenced drivers, hereafter referred as novice drivers [mean age: 25.2 years (± 4.3); mean number of post-baccalaureate years: 3.3 years, 4 females]. Two participants (one licenced) dropped the experiment and were not included in the analyses.

In the M condition, ten were licenced drivers, hereafter referred as experienced drivers [mean age: 23.8 years (± 3.4); mean driving experience: 5.6 years (± 2.7); mean kilometres driven per year declared: 9525 km (± 6804); mean number of post-baccalaureate years: 3.0 years, 5 females] and ten non-licenced drivers, hereafter referred as novice drivers [mean age: 25.4 years (± 3.3); mean number of post-baccalaureate years: 4.3 years, 3 females].

The protocol was approved by the Ethics Committee of Sud Méditerranée III (approval number 2019-A00646-51) and the methods were carried out in accordance with the relevant guidelines and regulations.

2.2. Automation

2.2.1. Assisted condition

In the A condition, a Lane Departure Warning System (LDWS) was included in the driving simulation as soon as the vehicle started moving. The device was perfectly accurate and delivered an auditory warning for

every lane departure. The warning sound was triggered when one of the front wheels of the simulated vehicle reached a lane marking (either on the left or right side of the driving lane). The warning onset was selected based on a series of previous experiments results in order to minimise the risk of false warnings (i.e. too early warnings to be perceived as correct) and maintain a good level of effectiveness (Navarro, Deniel, et al. 2019; Navarro et al. 2016, 2017). The warning sound was defined based on a previous work that showed its effectiveness (Lin et al. 2009). The sound delivered consisted in a 1-second sinusoidal pure tone at 1750 Hz with 6 bursts of 100 ms played at 84 dB, interspersed by 80 ms of silence. The warning sound was played bilaterally until the vehicle returned to a safe position in the driving lane.

2.2.2. Manual condition

The M condition is a control condition with the participants driving the same vehicle under the same conditions without LDWS.

2.3. Equipment

The experiment was conducted on a fixed-base simulator composed of three screens, providing a horizontal field of view of about 145°. The driving simulator was developed by the University of Sherbrooke (see Navarro, Osiurak, et al. 2019 for more details). The simulator was equipped with an automatic gearbox and included an adjustable seat (JCL Sim Racing), a steering wheel with force feedback, an accelerator, and brake pedals (Logitech G27). A speedometer was displayed at the bottom centre of the visual scene (Figure 1).

Gaze behaviours were recorded by means of an eye-tracker (iView X head-mounted, SensoMotoric Instruments) at a sampling rate of 50 Hz using a 9-point calibration procedure. Calibration accuracy was assessed by a visual check to ensure that all calibration fixations made by the participants were inside a circle of a 2° radius centred on each of the 9 calibration points. Fixations and saccades were segmented using a velocity threshold algorithm (I-VT Salvucci and Goldberg 2000) with a fixation velocity below 45°/s.

2.4. Procedure

Written informed consent was obtained from all participants.

Each of the six consecutive Experimental Weeks (EW) consisted in three simulated driving sessions.



Figure 1. Example of the visual scene during the bendy road drive.

One driving session was devoted to the experimental session itself (about 25 min) and the remaining two sessions (2×15 min) served as additional LDWS use in between experimental sessions. Whereas the same virtual environment was used for each of the six experimental sessions, participants were invited to drive in a variety of simulated environments during those complementary drives. Driving and gaze behaviours were recorded and analysed exclusively for the six experimental sessions.

Each experimental session was composed of three driving tasks: (i) highway drive, (ii) bendy road drive and (iii) a car following task. These three driving tasks were separated by driving in urban and peri-urban environments. Oncoming traffic was present at a rate of approximately two vehicles per kilometre.

At the beginning of the experiment, participants were presented with a short video demonstration of the LDWS. They were then asked to complete the UTAUT questionnaire (Venkatesh et al. 2003). They were also asked to complete the same UTAUT questionnaire at the end of the experiment.

2.5. Data analysis

2.5.1. Number and frequency of lane departure events

First, the total number of lane departure events has been analysed using a mixed-model ANalysis of VAriance (ANOVA) with Experimental Week (EW 1, 2, 3, 4, 5 and 6) as a repeated measures factor; and Driving Experience (Experienced drivers, Novice drivers) and

Automation (Assisted condition, Manual condition) as between-participant factors. This analysis offers an exhaustive overview of the results through time.

To allow an easier understanding of the results we defined and used a new factor in all subsequent analyses: Experimental Part, for which EW 1 and 2 were averaged together as the Initial Part of the experiment, and EW 5 and 6 as the Ending Part.

Second, lane departure frequency (i.e. number of lane departures per minute) was investigated using a mixed-model ANOVA with Experimental Part (Initial vs Ending Parts of the experiment) and Driving Task (highway, bends, car-following) as repeated measures factors; and Driving Experience (Experienced drivers, Novice drivers) and Automation (Assisted condition, Manual condition) as between-participant factors.

2.5.2. Steering behaviour

Third, the Duration of Lateral Excursion (DLE, i.e. the time out of the driving lane) was investigated using the same mixed-model ANOVA with Experimental Part (Initial vs Ending Parts of the experiment) and Driving Task (highway, bends, car-following) as repeated-measures factors; and Driving Experience (Experienced drivers, Novice drivers) and Automation (Assisted condition, Manual condition) as between-participant factors.

Fourth, Steering Reaction Time (SRT, i.e. time for the drivers' first action on the steering wheel after lane departure) was investigated using the same mixed-model ANOVA.

2.5.3. Visual behaviour

2.5.3.1. Spread of search. Fifth, the standard deviation of fixations coordinates was computed during lane departure events to describe the spread of search in both the horizontal and vertical axes, measures classically used to characterise drivers visual search (and see Robbins and Chapman 2019 for a recent review). The same mixed-model ANOVA was applied. The visual spread of searches metrics while driving have been introduced to investigate if drivers adopt general scanning strategies (Crundall and Underwood 1998). These metrics are known to be sensitive to driving experience (Crundall, Shenton, and Underwood 2004; Crundall and Underwood 1998; Konstantopoulos, Chapman, and Crundall 2010) and could be used to assess visual attention while driving (Crundall and Underwood 2011).

2.5.3.2. Mean fixation duration. Sixth, fixation durations during lane departure events were analysed through the same mixed-model ANOVA. Mean duration fixations are classically used as an indicator of the time taken to process gazed objects. The longer the fixation, the more demanding the associated cognitive processes, including in driving (Crundall and Underwood 2011).

2.5.4. Subjective assessment of the acceptance and use of technology

Seventh, UTAUT data, collected for the A condition only, were analysed through a mixed-model ANOVA with phase (before the experiment, after the experiment) and the eight dimensions of UTAUT (performance expectancy, effort expectancy, attitude towards using technology, social influence, facilitating conditions, self-efficacy, anxiety, behavioural intention to use the system) as a repeated measures factor; and Driving Experience (Experienced drivers, Novice drivers) as between-participant factors.

Tukey post-hoc tests were computed and a level of significance of $p < .05$ was used for all statistics. For sake of concision, only significant results were reported bellow.

3. Results

3.1. Lane departures events

3.1.1. Total number of lane departures

The results of the ANOVA revealed a significant effect of driving experience ($F(1,34) = 22.25, p < .001, \eta^2 = .40$), automation ($F(1,34) = 37.73, p < .001, \eta^2 = .53$) and experimental week ($F(5,34) = 8.41, p < .001, \eta^2 =$

.20; see Figure 2). For the main effect of Experimental Weeks, post-hoc analyses showed that EW 1 and 2 were all significantly different from EW 5 and 6 ($p < .05$).

On average, novice drivers committed more lane departures ($M = 39.5$) than experienced drivers ($M = 23.5$). Besides, in the A condition, drivers committed about 50% fewer lane departures ($M = 21.0$) than in the M condition ($M = 41.9$).

3.1.2. Lane departure frequency by driving task

The ANOVA revealed a significant effect of driving experience ($F(1,34) = 18.17, p < .001, \eta^2 = .35$; experienced drivers: $M = 2.98$ novice drivers: $M = 4.75$), automation ($F(1,34) = 29.00, p < .001, \eta^2 = .46$), experimental part ($F(1,34) = 4.41, p < .05, \eta^2 = .12$; Initial part of the experiment: $M = 4.15$; ending of the experiment: $M = 3.57$) and driving task ($F(2,68) = 14.08, p < .001, \eta^2 = .29$). Automation was also found to interact with driving task ($F(2,68) = 42.37, p < .001, \eta^2 = .56$; see Figure 3). Post-hoc analyses showed a significant difference between M and A conditions only for the bends and car-following driving tasks ($p < .05$).

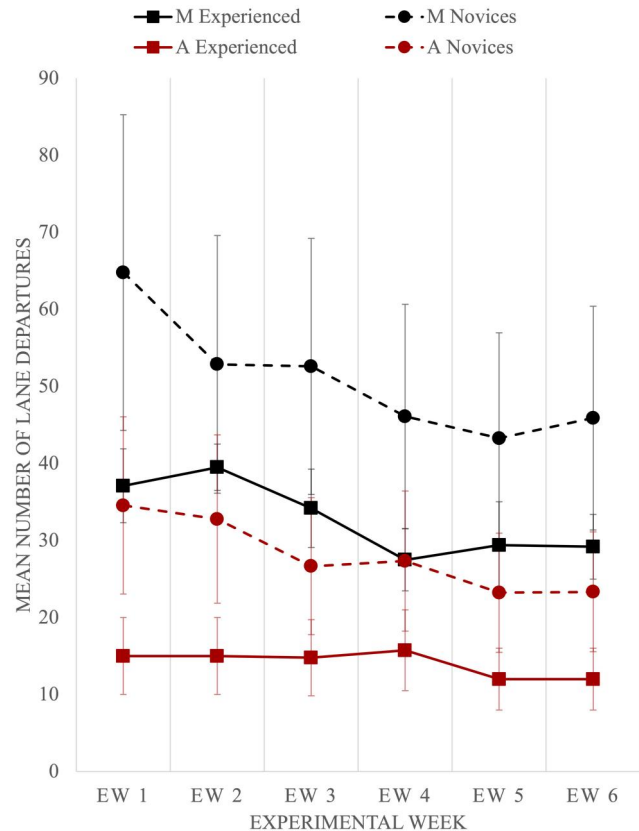


Figure 2. Mean number of lane departures per experimental week. Error bars represent standard errors.

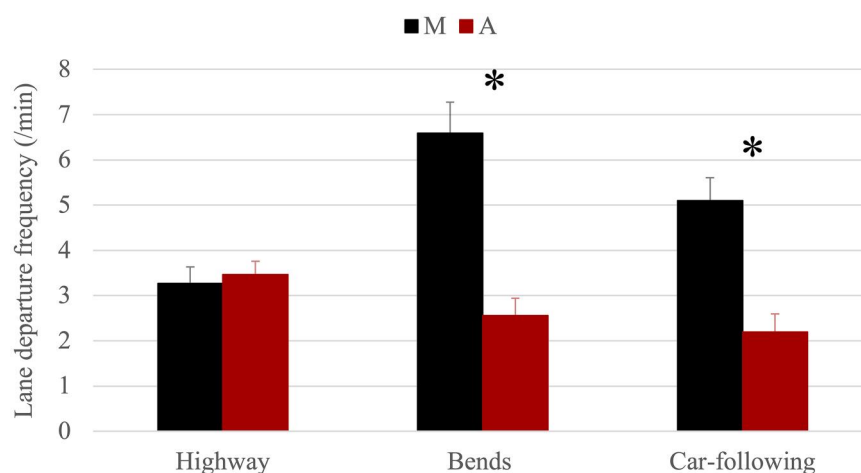


Figure 3. Lane departures frequency per driving task. Error bars represent standard errors.

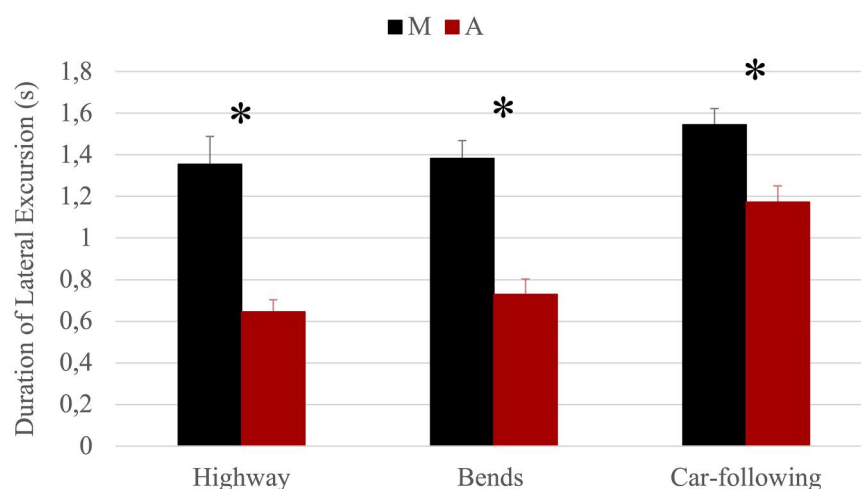


Figure 4. Duration of Lateral Excursion (DLE) per driving task. Error bars represent standard errors.

3.2. Steering behaviour

3.2.1. Duration of lateral Excursion (DLE)

The ANOVA revealed a significant effect of driving experience ($F(1,34) = 4.26, p < .05, \eta^2 = .11$; experienced drivers: $M = 1.05s$, novice drivers: $M = 1.22s$), automation ($F(1,34) = 48.83, p < .001, \eta^2 = .59$), experimental part ($F(1,34) = 4.63, p < .04, \eta^2 = .12$); initial part of the experiment: $M = 1.18s$; ending of the experiment: $M = 1.09s$) and driving task ($F(2,68) = 30.99, p < .001, \eta^2 = .48$). Automation was also found to interact with driving task ($F(2,68) = 6.89, p < .01, \eta^2 = .17$; see Figure 4). Post-hoc analyses showed a significant difference between M and A conditions for all three driving tasks ($p < .05$).

3.2.2. Steering Reaction time (SRT)

The ANOVA revealed a significant effect of the experimental part ($F(1,34) = 4.39, p < .05, \eta^2 = .11$); initial part of the experiment: $M = .29s$; ending of the

experiment: $M = .24s$) and driving task ($F(2,68) = 8.14, p < .001, \eta^2 = .19$). Automation was also found to interact with driving task ($F(2,68) = 9.33, p < .001, \eta^2 = .22$; see Figure 5). Post-hoc analyses showed a significant difference between M and A conditions only for the car-following task ($p < .05$).

3.3. Visual behaviour

3.3.1. Spread of search

The ANOVAs revealed a significant effect of automation (X-axis: $F(1,34) = 74.81, p < .001, \eta^2 = .69$; Y-axis: $F(1,34) = 46.83, p < .001, \eta^2 = .58$) and driving task (X-axis: $F(2,68) = 71.77, p < .001, \eta^2 = .68$; Y-axis: $F(2,68) = 8.17, p < .001, \eta^2 = .19$). Automation was also found to interact with driving task (X-axis: $F(2,68) = 4.07, p < .03, \eta^2 = .72$; Y-axis: $F(2,68) = 88.54, p < .001, \eta^2 = .11$; see Figure 6). Post-hoc analyses showed a significant difference between M and A conditions in X and Y axes for bends, and only in Y-axis for

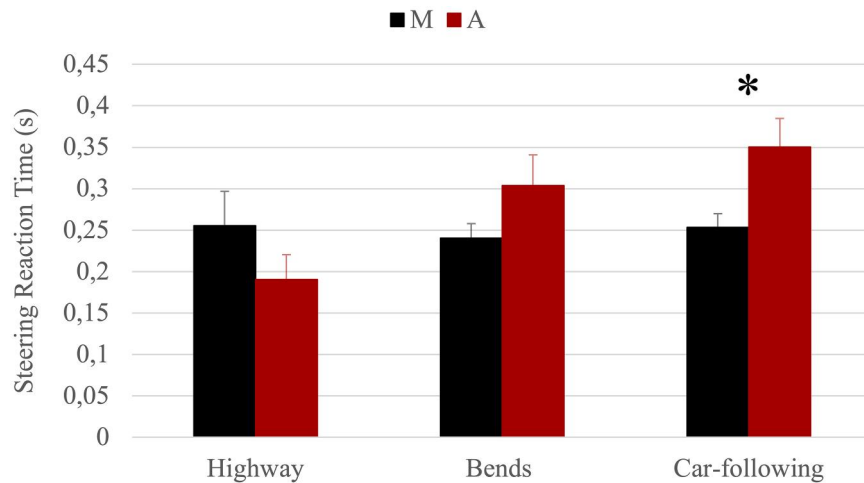


Figure 5. Steering Reaction Time (SRT) per driving task. Error bars represent standard errors.

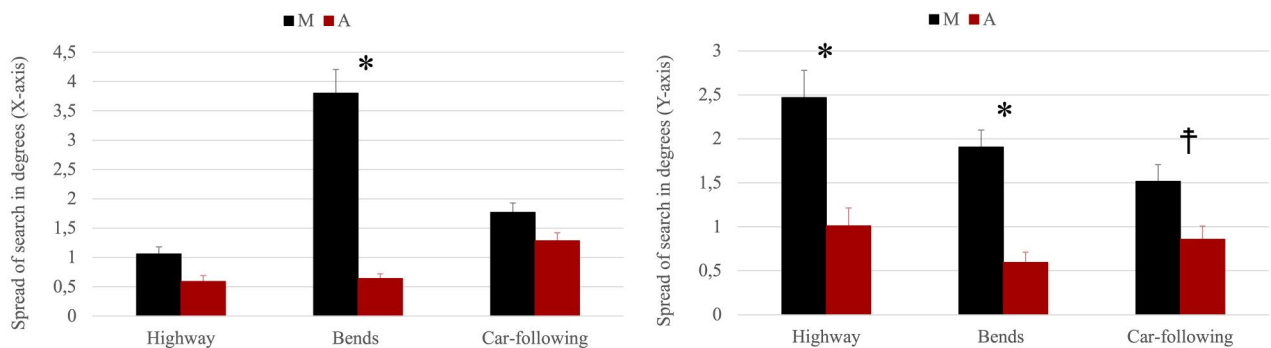


Figure 6. Spread of search in horizontal (X-axis, left) and vertical (Y-axis, right) axes per driving task. The significance mark on top of the car-following condition indicates the non-significant trend ($p < .1$). Error bars represent standard errors.

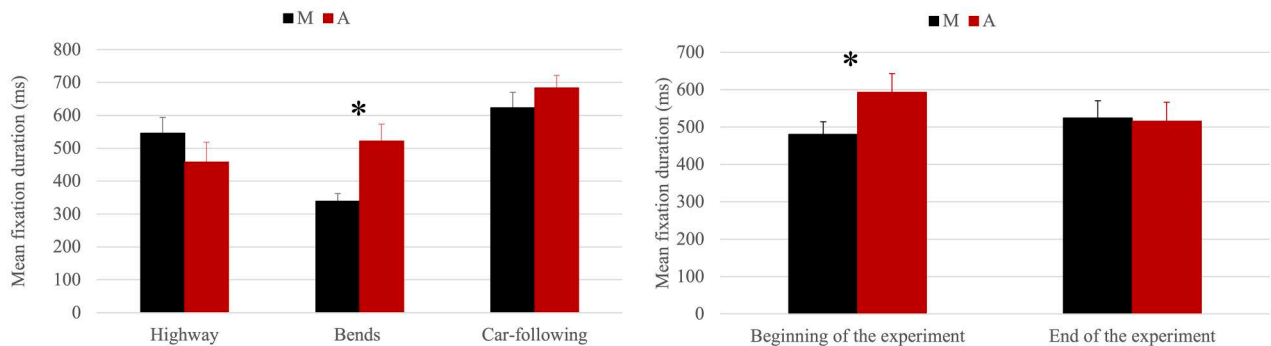


Figure 7. Mean fixation duration along driving tasks (left) and experimental weeks (right). Error bars represent standard errors.

highway ($p < .05$). A non-significant trend was also observed for the car-following task in Y-axis ($p < .1$).

3.3.2. Mean fixation duration

The ANOVA revealed a significant effect of driving experience ($F(1,34) = 74.81$, $p < .001$, $\eta^2 = .69$; mean experienced drivers: 478 ms, mean novice drivers: 579 ms) and driving task ($F(2,68) = 20.58$, $p < .001$, $\eta^2 = .38$) on the mean duration of visual fixations. Automation was also found to interact with the driving task and the experimental part (respectively

$F(2,68) = 7.24$, $p < .001$, $\eta^2 = .18$ and $F(1,34) = 8.95$, $p < .01$, $\eta^2 = .21$; see Figure 7). Post-hoc analyses showed a significant difference between M and A conditions for bends ($p < .05$, Figure 7, left) and at the beginning of the experiment ($p < .05$, Figure 7, right).

3.4. Subjective assessment of the acceptance and use of technology

The ANOVA revealed a significant effect of driving experience ($F(1,16) = 6.25$, $p < .03$, $\eta^2 = .28$; mean

experienced drivers: 3.70, mean novice drivers: 4.66) and phase of the experiment ($F(1,16) = 4.67, p < .05, \eta^2 = .23$; before the experiment: 4.37, after the experiment: 3.98).

4. Discussion

4.1. Lane departure episodes, steering and visual behaviours

The reported experiment aimed at investigating the impact of LDWS on lane departure events, steering, and visual behaviours in a simulated environment composed of three driving tasks (highway, bends, and car-following) over a 6-week period. Observations under LDWS presence (A condition) were compared with a baseline (M condition) without automation for both experienced and novice drivers.

The number of LD (Lane Departures) was dramatically reduced by LDWS, from an average of about 42 lane departure events in the Manual driving condition (M) to 21 in the Assisted driving condition (A). It should be noted that lane departure avoidance necessity was reinforced by the presence of oncoming traffic. A reduction of about 25% of LD was observed between the two first experimental weeks (mean LD: 37.1) and the two last experimental weeks (mean LD: 27.8). Besides, novice drivers were found to generate about 68% more LD than experienced drivers. Lane departure frequency was also found to be affected by the driving task considered, with less frequent LD events in the A condition, compared to the M condition, for the bends and car-following tasks but not for the highway driving task.

Regarding steering behaviours, LDWS reduced the Duration of Lateral Excursion (DLE) for all three driving tasks considered by about 40% on average. This drastic drop in DLE cannot be attributed to faster SRT. Indeed, while SRT was not significantly different for the highway and the bends driving tasks, warned LD produced greater SRT than unwarned LD for the car-following task. Also, shorter DLE and SRT were recorded for the last two experimental weeks as compared to the first two experimental weeks. Besides experienced drivers exhibited shorter DLE than novice drivers.

In terms of visual behaviours engaged during LD events, narrower horizontal and vertical spreads of search were recorded with LDWS (A) than without (M). While experienced drivers had shorter duration fixations compared with novice drivers, LDWS did not reduce the duration of fixations. On the reverse longer fixations were observed for the A condition than for

the M condition in bends, although no significant differences were found for highway and car-following tasks. Moreover, longer fixations were recorded with LDWS during the initial experimental part compared to the ending experimental part. This could be interpreted as an extra processing cost during the first interaction with warnings that vanishes over time.

4.2. The cognitive processes behind LDWS effectiveness

When considering these results together, the reported data confirm LDWS effectiveness. As previously observed (Deroo, Hoc, and Mars 2012, 2013; Hoc et al. 2006; Navarro et al. 2010, 2016, 2017; Navarro, Mars, and Hoc 2007; Rimini-Döring et al. 2005; Suzuki and Jansson 2003), LDWS reduced the number, frequency, and DLEs of the lane departure events. On average, LD events were reduced by half with LDWS and the DLEs for the remaining LD were about 40% shorter. Clearly, LDWS helped drivers to improve lateral control and to spend less time in an unsafe lateral position. This reinforces LDWS's usefulness to improve road safety and extends this observation for a prolonged period of 6 weeks without erosion over time. These new data emphasise real-world observations that found an LDWS-related accident reduction of about 50% compared to unassisted vehicles (Hickman et al. 2015; Sternlund et al. 2017).

Furthermore, and contrary to previous findings (Kozak et al. 2006; Navarro et al. 2016, 2017; Navarro, Mars, and Hoc 2007; Rossmeier, Grabsch, and Rimini-Döring 2005), SRTs were not smaller for warned LD. Nonetheless when considering auditory warnings, LDWS were not systematically reported as reducing SRTs (Navarro, Deniel, et al. 2019; Navarro et al. 2010). Thus, SRTs reduction is not as systematic as DLEs reduction. This finding has several implications.

First, LDWS benefits in terms of DLEs reduction are not supported by reduced SRTs. In other words, the benefits of LDWS are not mainly driven by a faster steering response due to a general speed-up of drivers' latency, situation diagnosis, and action control.

Second, SRTs and DLEs are revealing different drivers' internal processes engaged during lane departure events. SRTs designate drivers' latency to lane departure while DLEs are indicating the global steering manoeuvre quality, relying on situation diagnosis and action control (Navarro, Deniel, et al. 2019). DLEs are under the influence of each specific LD event, particularly the driving task considered. While mean DLEs recorded on highways and bends were not statistically

different (mean DLEs in bends were 54 ms longer than mean DLEs on highways), mean DLEs were significantly longer of about 330 ms during the car-following task. This result suggests that situation diagnosis required more time to be completed for the most demanding car-following task. This interpretation is reinforced by the fact that the mean of fixation durations was longer during the recovery manoeuvre in the same car-following task compared to other driving tasks (653 ms during car-following task vs. 466 ms in the other two driving tasks).

Third, LDWS systemically reduced DLEs while SRTs reduction seemed to be under the influence of the driving situation, manipulated here through the driving task. Here SRTs were even found significantly longer with LDWS for the most demanding driving task considered (i.e. car-following). In the case of a demanding driving task (here, the car-following task), the increased SRTs may indicate a change in the set of rules to be applied for determining the driver's behaviour in case of imminent lane departure.

In demanding driving situations, drivers may rely more on LDWS and thus monitor less the lateral position of their vehicle to focus on the longitudinal control required to perform the car-following task. This explanation would be consistent with the visual patterns engaged while performing a car-following task, mostly oriented towards the leading vehicle and speed adjustments (Navarro, Lappi, et al. 2021).

Fourth, the literature described SRTs as insensitive to the LDWS reliability, in such a way that previously unwarned, unnecessarily warned, or correctly warned lane departures events have no effect on the following SRTs (Navarro, Deniel, et al. 2019; Navarro et al. 2016). This is in line with a systematic drivers' latency improvement for warned LD (Navarro 2017). In the reported findings, participants experienced frequent LD events, resulting in repeated auditory warnings. Moreover, as LD events were not generated experimentally, not all LD events were unintentional, rather some could have been intentional (e.g. cutting bends) or due to poor steering abilities (e.g. over- or understeering in bends). The combination of LD high frequency with potentially intended LD could have led to a loss of benefits of the warnings delivered at the attention and perception module of the human-machine cooperation model of LDWS (Navarro 2017). Indeed, no current task interruption and motor response pre-activation would be required if the drivers were not distracted or engaged in another task, and that would be the case if the LD was intentional. This is in line with the findings demonstrating that

warned LD elicited shorter and less severe LD compared to unwarned LD for distracted drivers, but not for undistracted drivers (Gaspar and Brown 2020).

Besides, LDWS improvements were hypothesised to be supported by a reduction of the visual spread of search and faster visual processing of the driving scene in case of a lane departure event, thanks to the visual attentional guidance provided by the LDWS. This hypothesis is only partly validated by the data. In line with the hypothesis, a narrower spread of search was recorded for warned LD, particularly for bends in the horizontal dimension. Indeed, in the bendy road driving task, a large horizontal spread of search could be engaged by drivers due to the road curvature towards the left or right depending on the bend direction (Mars and Navarro 2012; Mecheri, Mars, and Lobjois 2022). In that same bends driving task, longer means of fixation duration were observed with LDWS than without, in opposition to the hypothesis. Thus, LDWS did not produce faster visual processing, and the reverse was even observed in bends. In the particular case of LD, an explanation would be that drivers gazed at the different elements of the driving scene not only to assimilate fixated objects (Crundall and Underwood 1998) but also to regulate the vehicle trajectory (Louveton, Montagne, and Berthelon 2018; Louveton et al. 2012; Navarro, Lappi, et al. 2021). This would explain the absence of faster visual processing with LDWS: visual fixations could be related to dynamic steering control and not exclusively to the processing of fixated objects. Nevertheless, longer means of fixation duration were observed with LDWS at the beginning of the experiment (593 ms) compared to the end of the experiment (516 ms) and without LDWS (see Figure 7, right). This might reflect a cognitive processing cost of the initial use of LDWS, a cost also observed in partly automated driving (Louv and Merat 2017). Drivers may exhibit longer visual fixations to ensure the warning delivered was correct.

4.3. Driving experience

A general effect of driving experience was observed for all indicators but SRTs and visual spread of search. Experienced drivers produced less LD, has less frequent LD, shorter DLEs, and shorter mean fixation duration. Unexpectedly, no interaction with LDWS was found. The absence of driving experience influence on SRTs and visual spread of search supports the previous interpretation about the experiment-specific loss of benefits of LDWS for the attention and perception module of the human-machine cooperation model of

LDWS. Furthermore, extending on the cognitive load hypothesis, novice drivers were expected to benefit more from the LDWS because driving should be more demanding for them than for experienced drivers (Engström et al. 2017). Such findings were not observed whatever the variable considered. This data tends to indicate that both experienced and novice drivers deal with LD using a similar set of rule-based behaviours. This suggests that skill-based behaviours are not engaged during LD events even for experienced drivers.

On the subjective side, novice drivers rated the LDWS as more acceptable than experienced drivers, suggesting that novice drivers were more likely to use automation than experienced drivers. This trend has already been observed for warning automation (Navarro, Allali, et al. 2021). LDWS acceptance level was lower after the experiment than before. This finding may indicate that automation was deceiving, in line with the low levels of use or activation observed in real-life driving (Braitman et al. 2010; Eichelberger and McCartt 2014; Reagan and McCartt 2016).

4.4. LDWS use over time

A major strength of the reported experiment was the investigation of LDWS use over 6 weeks. The longitudinal component of the study was found to be significant in terms of number and frequency of LD, DLEs, SRTs, and subjective assessment. All the measures collected but visual behaviours improved over time. However, no significant interaction between A and M groups were found, indicating that these improvements were not specific to the LDWS use but rather general. A positive formulation of these findings would be that the LDWS benefits remain stable during a prolonged use of the LDWS.

4.5. Refinement of the LDWS model and future perspectives

To conclude the discussion, the following lines offers a synthesis of the reported findings usefulness to refine the LDWS model (Navarro 2017). Driving experience was found to influence warned and unwarned LD in a similar way: this finding underlines the influence of driving experience on driving performances. Surprisingly, no specific influence of driving experience on LDWS was found. Driving situation, manipulated here through the driving task variable, was observed to have a major impact on visual and steering behaviours. This confirms that specific driving tasks engage

specific cognitive processes (Michon 1985; Navarro, Reynaud, and Osiurak 2018), even in the specific case of LD events. Regarding the information processing stages, LDWS offered a visual attentional guidance (i.e. narrower visual spread of search), even if no specific methodology was used to distract drivers from the driving task. Such effect on gaze strategies, associated with the attention and perception module of the model, might indicate that LDWS have not only the potential to redirect attention (Ho and Spence 2009; Spence and Ho 2008) but could also guide drivers gaze during the recovery manoeuvres. Further experiments are required to confirm and detail this possible interpretation. The situation diagnosis and control module of the model was confirmed to be mainly rule-based even for experienced drivers after prolonged use of the warning automation. Importantly, the dynamic nature of the model has also been investigated thanks to the longitudinal dimension of the experiment. Drivers' acceptance of LDWS lowered after automation use, but LDWS effectiveness remained stable during prolonged use.

No LD induction methodology was used. Consequently, we had no experimental control on the exact location and duration of LD events as well as on the attentional state of the drivers (distracted or not). This methodological choice was made to investigate LD events as they occur in everyday life. When a warned LD occurs, the diagnosis of the situation can either be triggered externally by the warning or internally by the driver him/herself if the imminent LD has been noticed before the warning delivery (according to Hoc and Amalberti 2007 terminology). This point is critical as it would impact the cognitive processes, as well as visual and steering behaviours, engaged to handle the considered LD. A limit of the current data is therefore the impossibility to distinguish whether only the LDWS noticed the LD, or if the driver also did so in parallel. This point could be related to the deactivation of LDWS in real life, as drivers may be annoyed by warnings of previously noticed LD.

5. Conclusion

The reported experiment offers new insights on LDWS use over time as compared to unassisted driving. The immediate benefits previously reported with LDWS have been confirmed with a major drop in the number of lane departure events and less time spent out of the driving lane limits. Those benefits do not vanish after several weeks of use: at the reverse, fewer lane

departure events were observed for the last 2 weeks of the experiment compared to the first 2 weeks. The spread of visual search was narrowed for warned lane departures compared to unwarned lane departures, indicating that the warning guided drivers' visual attention, allowing them to effectively diagnose the situation and have a more effective steering control. Altogether the results confirm the effectiveness of LDWS in terms of road safety and allow a better understanding of the associated human-machine cooperation processes.

Authors contributions

J.N., E.R., and D.S. developed the research question. J.N. and E.R. design the experimental task and protocol. J.N., E.R., M.P., and D.S. performed the experiment. J.N. and D.S. analysed the data. J.N. wrote the manuscript with input from E.R., M.C.O., C.G., and D.S. All authors approved the final version of the manuscript.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, J.N., upon reasonable request.

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