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Jordan Navarro, Emanuelle Reynaud, Catherine Gabaude. Eye-movement analysis in dynamic scenes: presentation and application of different methods in bend taking during car driving. *Le travail humain*, 2017, 80 (3), pp.307-330. 10.3917/th.803.0307 . hal-01701546

**HAL Id: hal-01701546**

**<https://hal.science/hal-01701546>**

Submitted on 5 Feb 2018

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Rubrique choisie: Techniques

Title: EYE-MOVEMENT ANALYSIS IN DYNAMIC SCENES: PRESENTATION AND APPLICATION OF DIFFERENT METHODS IN BEND TAKING DURING CAR DRIVING.

Short title: EYE-MOVEMENT ANALYSIS IN DYNAMIC SCENES.

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Signs count: 70330

Figures equivalent signs count: 10600 (3 x 1/3 page & 2 x 1/3 page)

Total: 80930

Abstract:

Eye movements analysis offers the possibility to investigate what is behind the eyes: our brain. Among the variety of activities studied by cognitive ergonomics, car driving received particular attention regarding visual exploration. Here, the four main techniques used to analyse eye movement data while driving have been applied to gaze positions analysis while negotiating bends under manual and highly automated driving. Gaze positions of eighteen drivers were recorded on a driving simulator. (1) Gaze plots and (2) areas of interest analysis based on the visual screen (without information on displayed images) did not reveal detailed differences between manual and highly automated driving, whereas (3) dynamic areas of interest and (4) dynamic point based on a dynamic element of the driving scene showed a disengagement from visual information required to steer the vehicle in bends in highly automated driving.

Key words: Eye movement, evaluation methodology, moving images, car driving, cornering behaviours.

## Résumé : ANALYSE COMPARÉE DES MOUVEMENTS OCULAIRES DANS LES ENVIRONNEMENTS DYNAMIQUES : PRÉSENTATION ET APPLICATION DES DIFFÉRENTES MÉTHODES À LA PRISE DE VIRAGE EN CONDUITE AUTOMOBILE.

L'oculométrie est une technique qui offre l'opportunité d'investiguer, au travers des mouvements des yeux, ce qui se trouve derrière : notre cerveau. Comme de nombreux autres domaines, l'oculométrie moderne bénéficie à la recherche en psychologie ergonomique. Parmi la variété des situations étudiées en psychologie ergonomique, l'activité de conduite automobile a fait l'objet de nombreuses études dont un bon nombre font appel à l'oculométrie. Les analyses des données oculométriques ont progressé à mesure du développement de cette technique, et sont aujourd'hui nombreuses et abouties en ce qui concerne l'analyse des parcours oculaires sur des images statiques. En revanche, dans le cadre de l'étude de la conduite automobile, comme des activités dynamiques en général, les images présentées au conducteur sont dépendantes à la fois de l'environnement de conduite, mais aussi de ses propres actions sur le véhicule via le volant et les pédales, ce qui rend les techniques d'analyse habituelles des données oculométriques peu pertinentes.

Face à cette situation, les chercheurs ayant un intérêt pour l'étude de la conduite automobile ont développé plusieurs techniques d'analyses des mouvements oculaires qui peuvent être regroupées en quatre classes de méthodes. Les quatre méthodes se définissent par rapport à l'analyse des positions du regard (1) dans un référentiel écran (sans indication sur ce qui est visible dessus) en deux dimensions, (2) selon des zones d'intérêts fixes définies dans ce même référentiel écran, (3) selon des zones d'intérêts dynamiques définies dans un référentiel relatif à la tâche de conduite (un élément de la scène visuelle qui se déplace dans celle-ci) et (4) dans un référentiel défini sur un point dynamique de la scène visuelle (un point de la scène visuelle qui se déplace dans celle-ci).

Chacune de ces quatre classes de méthode a été présentée et appliquée ici à la prise de virage en conduite automobile simulée en condition de conduite classique et en conduite hautement automatisée. En condition hautement automatisée, l'assistance maintenait le véhicule dans sa voie en agissant directement sur le volant sans aucune intervention de la part du conducteur. Dix-huit conducteurs ont pris part à une étude sur simulateur de conduite où les positions du regard ont été enregistrées. Selon la méthode d'analyse considérée, les résultats obtenus varient considérablement. A l'appui des résultats d'analyse collectés via les quatre classes de techniques d'analyse, les analyses relatives à un point ou une zone dynamique dans la scène visuelle sont apparues les mieux adaptées à l'analyse des données oculaires en contexte de conduite automobile. Ce sont les seules méthodes qui ont permis de mettre en avant et de spécifier une différence dans les prises d'informations visuelles en présence de l'assistance et comparativement à la condition non-assistée. La discussion présente les avantages et les limites de chacune des quatre classes de méthode et l'impact du choix de la méthode d'analyse des données oculaires sur l'analyse ergonomique des situations considérées et les enjeux sécuritaires associés.

Mots clés : Mouvements oculaires, méthodologie d'analyse, images animées, conduite automobile, prise de virages.

## I INTRODUCTION

“Les yeux sont les fenêtres de l’âme” or “Eyes are the windows to the soul” for a translation, Georges Rodenbach.

This citation illustrates an old idea that eyes might offer a special access to human cognition. Indeed, it is known for long that the eyes and the mind are tightly linked. Consequently, eye movements have always been of interest so as to investigate what is behind the eyes: our brain. This idea has been put into practice numerous times in a variety of tasks such as reading, music reading, typing, visual search, and scene perception. Based on a literature review on these different topics, with a major emphasis on reading, researchers concluded that “eye movement data reflect moment-to-moment cognitive processes in the various tasks examined” (Rayner, 1998). Other researchers also found anatomical relationships between eye movements and cognitive processes. Eye movements and attention share anatomical bases in the brain for instance (Corbetta et al., 1998), reinforcing the idea that eye movements might allow to understand the brain quite directly.

Even if modern eye-trackers have been expanding rapidly for about two decades, eye-tracking techniques started in the early 1900s. The educational psychologist Edmund Burke Huey is known to have built what is often referred to as the first eye-tracker in 1908. This eye-tracker was designed to study reading and was very intrusive, as readers had to wear contact lenses with holes for the pupils. The lenses were attached to a pointer which followed eye movements, revealing them to the experimenter (Huey, 1908). Since that very first idea, eye-tracking techniques have improved with the sophistication of the tools available to record eye movements and particularly the development of video cameras. Nowadays, eye-tracking techniques are very accurate and relatively easy to implement in real life activities. Depending on the activity considered, people do not have to wear any apparatus directly, the video cameras used to record eye movements can be located inside a computer screen or in front of the person of interest. Other techniques sometimes require people to wear a helmet linked to a computer or even more recently glasses linked to a smartphone for instance.

As many other domains, including cognitive and educational psychology or marketing among others, cognitive ergonomics benefit from those techniques improvements. Among the variety of activities studied by cognitive ergonomics, an activity that appeared after Huey’s first eye tracker received particular attention regarding visual exploration analysis: car driving. Because most of the driving activity is based on visuomotor coordination, researchers focusing on car driving had a direct interest to understand visual explorations of the driving environment. This led early car driving researchers to suggest that eye movements analysis may be the best method to assess driving behaviours (Walraven & Lazet, 1966). The first eye-tracking experiment carried out on car driving studied the impact of route familiarity on visual patterns, showing an increase of gaze positions compactness with the increase of route familiarity (Mourant &

Rockwell, 1970). Caution must be taken when interpreting eye-tracking data, because those devices only focus on central vision and no information on peripheral vision is collected. This limitation of eye-tracking method has been pointed out since the first eye-tracking experiment on car driving (Mourant & Rockwell, 1970; Rockwell, 1972). This is particularly important in the context of car driving because it is known for long that peripheral vision participates to car steering by monitoring the lane edge markers for instance (Mourant & Rockwell, 1970; Summala, Nieminen, & Punto, 1996).

Driving is composed of three main sub-tasks: control, navigation and hazard identification (Stanton, Young, Walker, Turner, & Randle, 2001). Control refers to car steering and speed adjustment, navigation refers to planning the journey and hazard identification to the detection of potential hazard. All these sub-tasks rely on visual analysis of the driving scene. Therefore, these three driving sub-tasks can benefit from visual exploration analysis. Among these three sub-tasks, eye-tracking offered an important contribution to the understanding of car control, in particular since the seminal work on drivers eyes positions while steering the car in bends (Land & Lee, 1994). These authors observed that during bend taking, drivers spent about 75 percent of the time looking around a particular region of the driving environment. This particular region was referred as the Tangent Point (TP), a dynamic point changing according to the driver position but that remained located “on the inside of each bend, where the edge of the road reverse direction” (Land & Lee, 1994). This result was replicated several times and drivers indeed spend between 50% and 75% looking in the TP area while negotiating bends (Kandil, Rotter, & Lappe, 2009; Mars, 2008; Panerai, Toffin, Paille, Kemeny, & Fadel, 2007; Wilson, Stephenson, Chattington, & Marple-Horvat, 2007). The TP area might be looked at by drivers because (1) this particular point of the road might indicate directly to the driver the curvature of the bend (Land, 2001), (2) this particular point of the road corresponds to the vehicle future trajectory and is therefore a point followed by drivers (Wann & Swapp, 2000; Wilkie & Wann, 2003).

Analysis of car driving, and particularly steering control has benefited from the use of modern eye-tracking techniques. But eye-trackers have been initially designed to record and analyse gaze positions on still images. These devices are therefore perfectly adapted for cognitive activities such as reading. For instance, in a reading task, a page composed of text and/or images is displayed for a period of time and the reader’s visual exploration of this page is analysed. However, cognitive activities relying on moving images are also of interest. For instance, and as introduced previously, a large community in the cognitive ergonomics field is working on car driving, involving moving images situations. For car driving, as in any dynamic environment, the images (i.e. visual driving environment) are not only changing repeatedly in a defined order as in a video but also depend on the drivers’ actions. The driving scene available to the driver at any time depends upon the environment itself (like in the reading example) but also upon the driver’s actions on the vehicle controllers (steering wheel and pedals). Depending

on the driven vehicle position on the road, the visible driving scene is different. As soon as the driver turns the steering wheel for instance, the visible driving scene is changing. To illustrate this point, when driving in straight lines, the road visible to the driver is mostly in front of him/her but when negotiating bends, the road visible is mostly on the right of the driver in a right bend and on the left of the driver in a left bend. These modifications of the driving environment cannot be predicted prior the drive itself because they depend on the driver behaviours at all times.

The softwares developed by eye-trackers manufacturers to analyse gaze data were designed to analyse precisely activities relying on still images. These softwares are not adapted to dynamic environments such as car driving because the dynamic nature of images displayed is not taken into account. When considering still images, some of the most popular gaze positions analysis are gaze plots, scanpaths, areas of interests and heat maps (Gitelman, 2002; Holmqvist et al., 2011). Gaze plots are a representation of the eyes positions when scanning a visual scene. Scanpaths can be defined as eye positions trajectory when scanning a visual scene, here the chronology of the eyes positions is considered (Noton & Stark, 1971a, 1971b). Areas of interest are areas defined on the visual scene where eye movements data are analysed. Heat maps offer a representation of gaze positions by separating the different levels of observation intensity (Špakov & Miniotas, 2015). In the case of a dynamic environment, these softwares and associated techniques can still be used to analyse gaze positions. Nevertheless, in this particular case, the moving images display (real or virtual) is only used as a system of reference and the images themselves are not taken into account. This is a serious limitation when it comes to data interpretation, because looking to the right of the driving scene for instance has a different meaning depending of the visual environment available (e.g. looking at pedestrians about to cross the road or looking at advertising billboards). These gaze position analyses remain valid even in dynamic environments if researchers only focus on visual parts of the driving scene that do not change over time such as the speedometer or other dashboard elements (e.g. Victor, Harbluk, & Engström, 2005).

Because eye-trackers softwares are not designed to take into account moving images especially when the images displayed are dependent of the subject actions (e.g. simulated or real car driving situation where the visual environment depend on drivers' actions on the steering wheel and pedals), an actual challenge for researchers dealing with dynamic situations such as car driving is to analyse eye movement data taking into account the dynamics of the situation. Through the years, several options have been imagined to extract the meaningful information from the collected data in dynamic environments. Here the focus is set on car driving, but the methods used are relative to gaze position analysis, and therefore potentially transferable to all other dynamic situations.

As a mean to escape from the difficulty of dynamic environment and to collect accurate eye movements data, some researchers made successive pictures of the driving situations of interest and then recorded eye movements when drivers were confronted to those pictures. Using this methodology, drivers were found to gaze at cyclists when facing at a T-junction before any other relevant area (Walker & Brosnan, 2007). Even if this idea is a clever attempt to explore visual scanning in a dynamic environment, it obviously limits the interactions of the driver with his/her environment to the few selected images.

Apart from that methodology, four main eye movements analysis techniques have been identified from the driving literature:

(1) **Gaze plots** are the representation of gaze positions over a period of time (Konstantopoulos, Chapman, & Crundall, 2010; Wilson et al., 2007). This type of analysis is rough because it does not take into account the visual elements available on the driving scene but simply the driving scene as a frame of reference.

(2) **Areas of interest**, visual areas defined by an expert as relevant for performing a goal-oriented task. Within the context of car driving, AOIs are visual areas, defined on the driving scene, that researchers judged as relevant for performing the driving task and worthwhile analysing regarding eye movements. These Areas Of Interest (AOI) are selected by the experimenters according to the objective pursued. Researchers may focus on a single AOI defined on the visual scene, such as the proportion of time fixating the road ahead (Edquist, Horberry, Hosking, & Johnston, 2011). The focus can also be put on several AOIs, for instance a “relevant” area for driving and another area used to display experimental cues (Megías et al., 2011). The entire driving scene may also be considered and divided into five AOIs for instance (Carsten, Lai, Barnard, Jamson, & Merat, 2012; Hughes & Cole, 1988). These researchers defined their five regions as (a) a circular 6° central region on the screen, (b) a left region covering a variety of elements such as a DVD screen, radio controls, the left side mirror, door window and traffic in adjacent lane, (c) a right region covering gaze positions to the right side mirror, door window, traffic in the adjacent lane and in the opposite carriageway, (d) a bottom region covering mainly the dashboard with a variety of gauges including the speedometer, (e) and a top region covering mainly the sky (Carsten et al., 2012). Finally, another option is not to define AOIs based on researchers’ expectations but rather to divide the entire driving scene in equal AOIs using a grid (Di Stasi, Contreras, Cándido, Cañas, & Catena, 2011) or to use density plots of gaze positions on the visual screen (Chapman & Underwood, 1998; Crundall, Van Loon, & Underwood, 2006).

(3) **Dynamic AOIs** allow accurate eye movements analysis within the context of dynamic environments. A dynamic AOI is an area that has different locations on the visual scene but follows the movements of an element of the visual environment. In that case, gaze positions are considered relatively to an element of the visual scene. Taking into account the dynamics of the



situation. Dynamic AOIs may be relative to visual objects of the driving environment (Salvucci, Liu, & Boer, 2001; Salvucci & Liu, 2002) or to invisible elements of the driving scene such as the tangent point (Land & Lee, 1994). Results may be represented on density maps (Land & Lee, 1994).

(4) Finally the fourth category, **dynamic point** is derived from the previous method, offering an analysis of gaze positions relative to a dynamic point on the visual scene but with extra precision and a decomposition of gaze positions in horizontal and vertical components (Mars & Navarro, 2012).

Within the actual context of highly automated driving and associated human-machine cooperation issues (Hoc, Young, & Blosseville, 2009; Navarro, Mars, & Young, 2011), an important question that cognitive ergonomics researchers have to address is how automation interfere with driving behaviours. Modifying the way drivers steer their cars may also have an impact on how they explore their environment. The focus was set on the influence of a highly automated vehicle (here the automation steered the car without any human intervention) on eye movements during bend taking. To do so, drivers gaze positions have been recorded in two experimental conditions: manual driving and automated driving, offering the opportunity to compare gaze positions distributions between the two conditions.

Here, the four main techniques used to analyse eye movements data while driving have been applied to gaze positions analysis while negotiating bends, under two conditions: manual and automated driving. Our objective was to evaluate the impact of the technique used on the assessment of gaze positions changes between manual (No Assistance -NA-) and automated driving (Assistance -A-). The underpinning objective is to help future researches to select the most appropriate technique to analyse eye movements in dynamic environments.

## II METHOD

### II.1 PARTICIPANTS

Eighteen drivers (16 men) with normal vision participated in this experiment. Their age ranged from 21 to 49 years old with an average of 27 years. None experienced simulator sickness.

### II.2 DRIVING SIMULATION

The experiment used a fixed-base simulator (SIM<sup>2</sup>, developed by IFSTTAR-MSIS). Participants took place in a driving seat and steered the vehicle through force feedback steering wheel and pedals (for more details, see Espié, Mohellebi, & Kheddar, 2003). The simulated driving environment represented a two-lane road similar to a typical French rural road composed of 13 bends linked the one to the other by straight lines. It took drivers about 3-5 minutes to complete the simulated circuit. No traffic was present during the experiment.

The driving scene was projected on a screen of 2.4 m width and 1.91 m height viewed by drivers at a distance of about 2 m. Thus the screen offered a 62° width by 51° height of field of view. A speedometer was displayed on the bottom left part of the screen.

### II.3 EYE TRACKER

A head-mounted IviewX system® video based/corneal reflexion tracker (Sensomotoric Instruments) equipped with a magnetic tracker (Polhemus®) were used to track drivers' gaze positions taking into account their head movements. Gaze positions were recorded at a frequency of 50 Hz, after a 13-points calibration procedure was performed.

### II.4 AUTOMATED DRIVING

Under automated driving, participants were provided a steering assistance that took over the lateral control task. In other words, the steering wheel was automatically turned on by the assistance in order to keep the vehicle on its driving lane without any action of the driver. The automation was designed by IFSTTAR-LIVIC on real cars (Chaib, Netto, & Mammari, 2004; Netto et al., 2003) and implemented on the driving simulator by IFSTTAR-MSIS. Drivers were instructed to keep both hands on the steering wheel, to get haptic feedbacks from automated actions through the steering wheel displacements. Participants kept manual control of the vehicle speed and adjusted it to negotiate the different bends of the virtual environment.

### II.5 PROCEDURE

Participants were instructed that they had to drive as they usually do (manual driving) and with a perfectly reliable automation that will steer the vehicle (automated driving). After a familiarisation with the driving simulator by performing the two first drives, the 8 experimental drives started. 4 consecutive drives were performed under manual driving and 4 under automated driving. The presentation order was counterbalanced between participants. All things considered, the experiment lasted about two hours, including eye tracker calibration, driving practice, experimental driving and breaks.

### II.6 DATA ANALYSIS

Eye movement data were analysed for two different bends, of similar curvature radius, of the experimental drives: a left bend with a curvature radius of 73 m, and a right bend with a curvature radius of 80 m. As the method used to analyse eye movement was different for each technique considered, specific data analysis material is available in the results sub-sections.

## III RESULTS

### III.1 GAZE PLOT

Gaze plot is the most straightforward eye movements analysis methodology, and is regularly used including in car driving studies (e.g. Konstantopoulos, Chapman, & Crundall, 2010; Wilson, Stephenson, Chattington, & Marple-Horvat, 2007). It simply represents all gaze positions collected for a given period of time on the visual screen without taking into account that the images displayed on the screen are permanently changing. Because of the great amount of eye movement data, representative examples are often presented for a single participant in the different conditions of the experiment. Here Figure 1 presents the data collected for one left bend (on the left side) and one right bend (on the right side) for a given participant without (NA: blue circles) or with automation (A: red diamonds).

If gaze plot examples represent nicely eye-movement data, their interpretation is particularly difficult when the visual scene is dynamic and depends on the participants' behaviours. The bottom part of Figure 1 illustrates the same gaze plot examples displayed in the top part of the figure but with a background image applied to the gaze plots. As any image used for that purpose, the illustration is not relevant because it is not possible to represent the visual scene accurately with a single image, due to the fact that the image is changing during the acquisition of eye movements. To illustrate that point, a background image representing the very beginning of the left and the right bend has been selected. It appears clearly that, apart for the glances at the fixed-position speedometer, the drivers' gaze positions were distributed over a part of the background image drivers had no reasons to look at. Therefore, it appears non relevant to represent them over a single, still image. With this type of representation, the interpretation of the results displayed is mostly dependent of the image selected to illustrate the results. For the considered examples it is hard to conclude on differences between NA and A driving. It seems that drivers looked more to the left of the screen in the left bend and more to the right of the screen in the right bend.

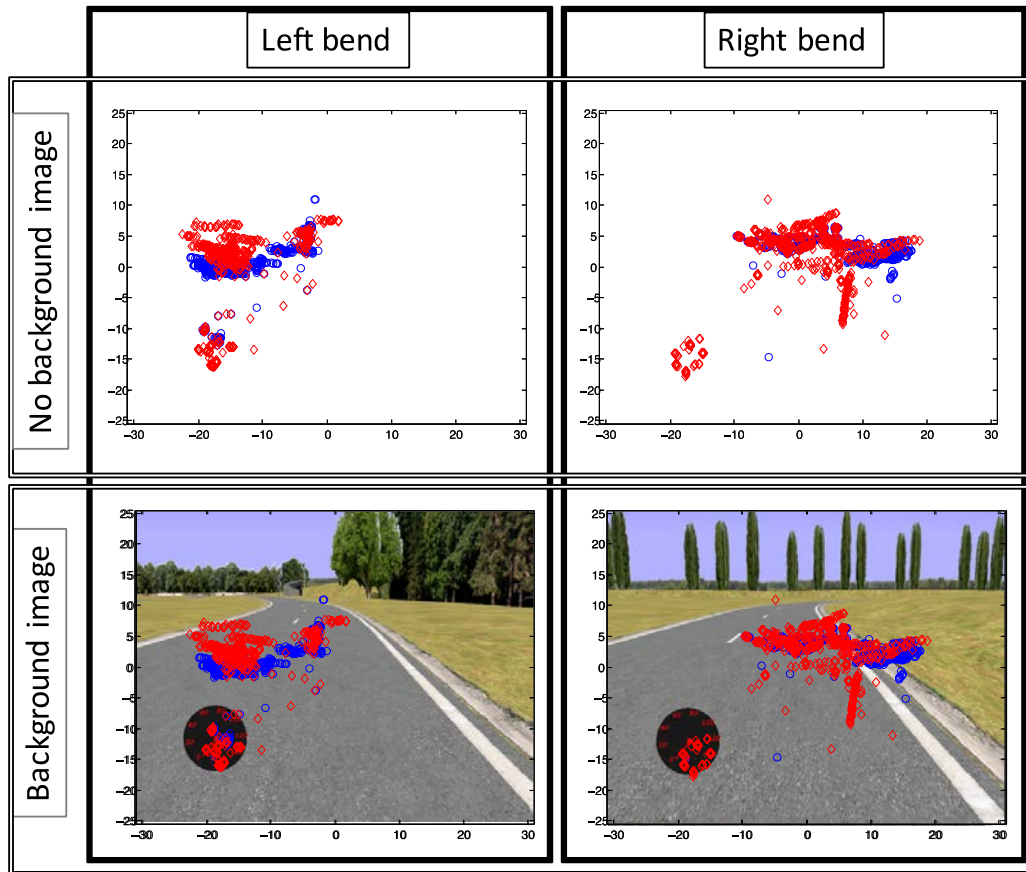


Figure 1: Example of gaze positions for a left bend (the two gaze plots on the left) and for a right bend (the two gaze plots on the right) for one participant. The blue circles represent the gaze positions collected in the No Assistance condition (NA) and the red diamonds the gaze positions collected for the Assisted condition (A). The top and bottom gaze plots are the same, an “unrepresentative” background image was simply added to pinpoint the lack of accuracy of this representation. All gaze plots are represented in degrees of visual angle relative to the screen where the driving scene was projected. The origin of the coordinate system is the centre of the screen. Positive values refer to the top and the right parts of the screen, negative values to the bottom and the left parts.

Figure 1 : Exemple de distribution des positions du regard dans la scène visuelle pour un virage à gauche (les deux graphiques situés à gauche) et pour un virage à droite (les deux graphiques situés à droite) pour un participant. Les cercles bleus représentent les positions du regard dans la condition Non Assistée (NA) et les losanges rouges les positions du regard dans la condition Assistée (A) où les participants se déplaçaient à l’aide d’un véhicule hautement automatisé prenant complètement en charge le guidage latéral de la voiture. Les deux graphiques situés en haut sont identiques à ceux situés en bas de la figure. Une image “non représentative” de la scène de conduite a simplement été ajoutée en arrière plan sur les graphiques du bas pour illustrer le manque de précision de ce type de représentations. Les positions du regard sont

exprimées en degrés dans un repère centré sur le centre de l'écran de projection de l'environnement de conduite virtuel. 0 sur l'axe des abscisses correspond au centre de l'écran horizontalement, une valeur positive indique un regard sur la partie droite de l'écran tandis qu'une valeur négative indique un regard sur la partie gauche de l'écran. 0 sur l'axe des ordonnées correspond au centre de l'écran verticalement, une valeur positive indique un regard dans la partie haute de l'écran tandis qu'une valeur négative indique un regard dans la partie basse de l'écran.

In order to complement this type of representations with statistical analysis, horizontal and vertical variability of gaze positions can be analysed (Konstantopoulos et al., 2010; Underwood, Crundall, & Chapman, 2011). In the current experiment, the average standard deviation of gaze positions for all drives in the NA and A conditions were computed (see Figure 2). Very different eye movements variability was collected in the considered left (below 10°) and right bend (above 15°). This indicates that visual exploration of the driving scene is largely dependent on the driving context. For the left bend, no significant difference between the assistance and the no assistance conditions was observed in the X-axis variability (NA-A;  $d=7-6.5= 0.5^\circ$ ;  $t(17)=.61$ ;  $p=.55$ ) and a small but significant difference was found for the Y-axis (NA-A;  $d=4.1-5.1= -1^\circ$ ;  $t(17)=3.07$ ;  $p<.007$ ). For the right bend, both the X-axis and Y-axis variabilities appeared to be significantly different between the assistance and the non assistance conditions (X-axis: NA-A;  $d=31.9-18.8= 13.1^\circ$ ;  $t(17)=3.79$ ;  $p<.002$ ; Y-axis: NA-A;  $d=38.7-28.7= 10^\circ$ ;  $t(17)=2.96$ ;  $p<.009$ ). Both horizontal and vertical variabilities were decreased in the assistance condition compared to the assistance condition.

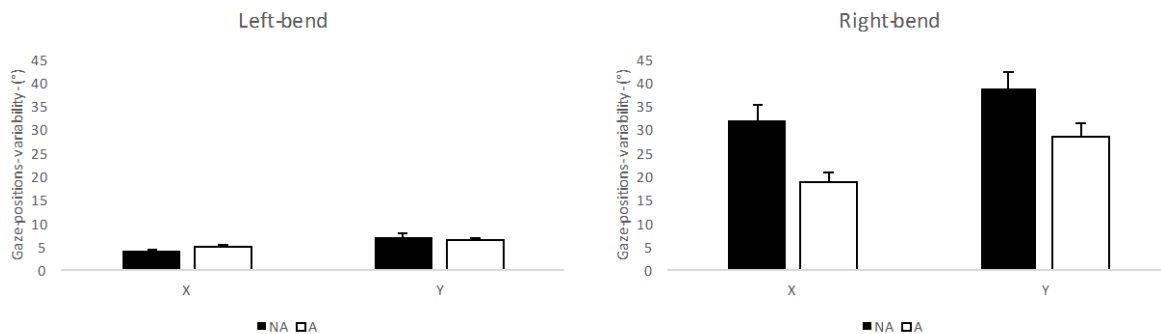


Figure 2: Gaze positions horizontal (X) and vertical (Y) variability in the assistance (A) and the no assistance (NA) conditions for left and right bends. The error bars represent one standard error.

Figure 2 : Variabilité horizontale (X) et verticale (Y) de la position du regard dans la scène visuelle avec assistance (A) et sans assistance (NA) pour le virage à gauche et le virage à droite considéré. Les barres d'erreur représentent l'erreur type.

## III.2 AREAS OF INTEREST (AOI)

### III.2.A On static parts of the environment

All the main eye-trackers and associated softwares available on the market offer the possibility to define easily AOI on the screen, although AOI definition can be a tricky exercise that requires researchers' expertise. As for gaze plots, this type of analysis is not particularly well suited to dynamic environments as the areas defined on the screen did not take into account the different images displayed on the screen. In other words, looking at a particular area on the screen is different from looking at a particular area on the images displayed (here the driving environment). It is more relevant, however, to analyse the AOI that are static in the driving environment such as the mirrors (e.g. Recarte & Nunes, 2003; Taoka, 1990) or in-vehicle signs for instance (Caird, Chisholm, & Lockhart, 2008).

Such an analysis was not the purpose of the current experiment because the focus was not set on the static parts of the environment. However, the speedometer was displayed at the bottom left of the screen at all times during the experiment. A brief descriptive analysis indicated that drivers gazed more often at the speedometer in the assistance condition compared to the no assistance condition (increase of 137% in gaze proportion on the left bend and of 37% in the right bend).

### III.2.B On dynamic parts of the environment

Some researchers use AOIs defined on the visual screen and based on their expectations to analyse eye movements while driving. Even if inaccurate by nature, this method might be acceptable under very restricted driving conditions such as driving in a straight lane or with very gentle bends and using roughly defined AOI to analyse eye movements (Carsten et al., 2012). However, a better option is not to consider any AOI prior to the experiment, but to explore eye movements based on the results collected (Di Stasi et al., 2011). Following this rationale the AOIs will emerge from the eye movement data, offering the possibility to compare different conditions.

Figure 3 presents four heat maps, each based on the normalized amount of gaze positions in the visual screen. The warmer the colour the more gaze positions were recorded at that particular location on the screen. The heat maps were computed by dividing virtually the screen in 400 potential AOIs (using a 20 x 20 grid). The number of gaze positions recorded in each of the 400 potential AOIs were added up over the total number of participants. The AOIs with the biggest gaze positions numbers were then coloured in the warmest colour (intense red) of the heat map, the AOIs with the smallest gaze positions numbers were coloured in the coldest colour (intense blue). From a general perspective each AOI was associated to a colour depending of the relative number of gaze positions received. In order to define the AOIs allowing a direct comparison between the colours represented in the four different heat maps, the number of gaze positions

collected for each potential AOI has been normalized between 0 and 1, 1 corresponding to the AOI that received the maximum gaze positions. As for gaze plots analysis, and even if the representation here is much richer because it includes all participants, it is hard to notice differences between NA and A conditions. Drivers looked more to the left of the screen in the left bend and more to the right of the screen in the right bend, confirming the observations made on gaze plots.

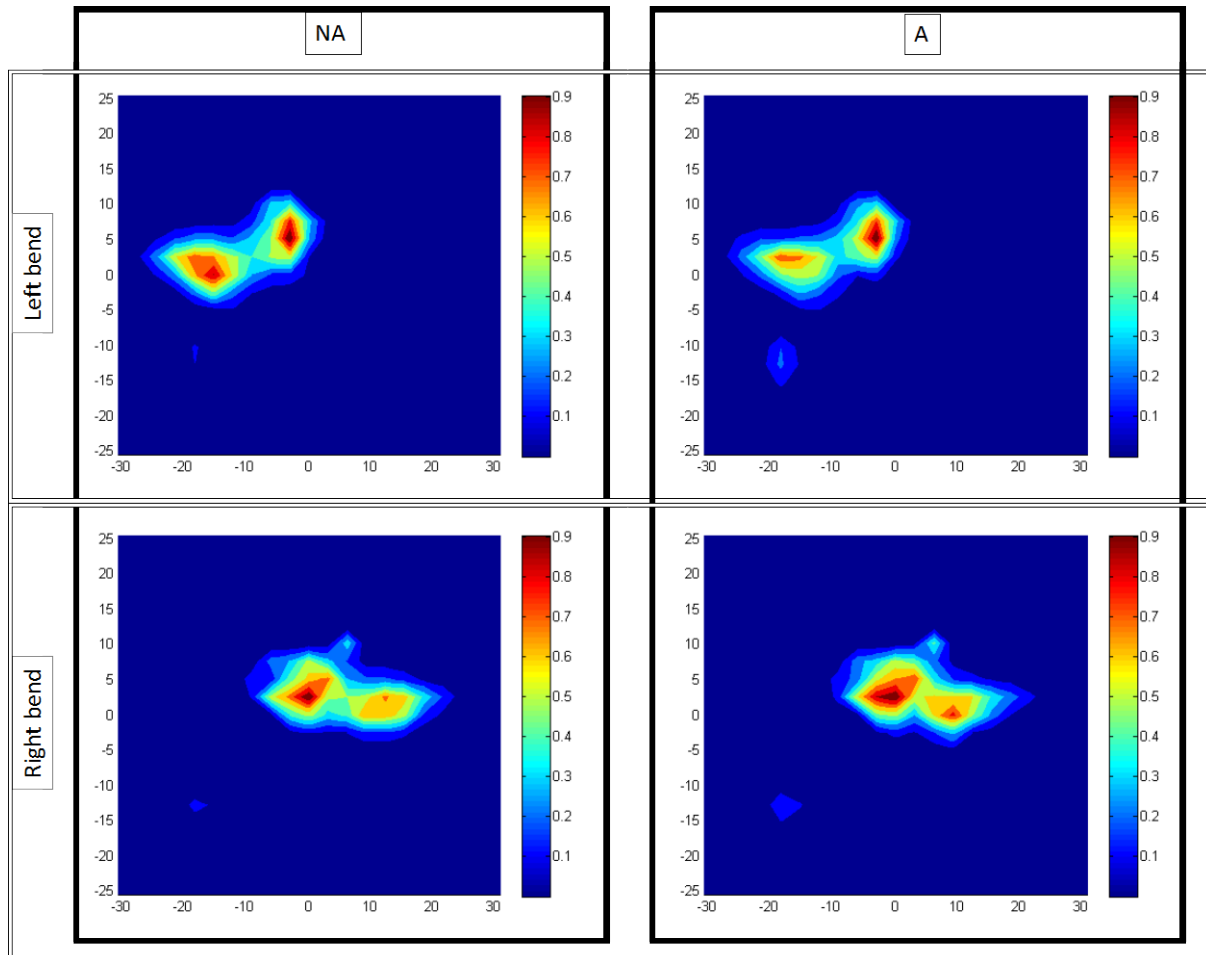


Figure 3: Heat maps representing all gaze positions collected for all participants. The two top graphs represent the left bend (NA on the left and A on the right). The two bottom graphs represent the right bend (NA on the left and A on the right). All gaze positions are represented in degrees of visual angle relative to the screen where the driving scene was projected. The origin of the coordinate system is the centre of the screen, top and right are positive values, left and bottom are represented by negative values. A normalized colour scale was set for the four heat maps. The warmer the colour the greater the number of gaze position received in that particular location of the screen.

Figure 3 : Cartes de chaleur représentant toutes les positions du regard recueillies pour l'ensemble des participants. Les deux graphiques situés en haut représentent le virage à gauche (en condition non assistée à gauche et avec un véhicule hautement automatisé à droite). Les

deux graphiques situés en bas représentent le virage à droite (en condition non assistée à gauche et avec un véhicule hautement automatisé à droite). Les positions du regard sont exprimées en degrés dans un repère centré sur le centre de l'écran de projection de l'environnement de conduite virtuel. 0 sur l'axe des abscisses correspond au centre de l'écran horizontalement, une valeur positive indique un regard sur la partie droite de l'écran tandis qu'une valeur négative indique un regard sur la partie gauche de l'écran. 0 sur l'axe des ordonnées correspond au centre de l'écran verticalement, une valeur positive indique un regard dans la partie haute de l'écran tandis qu'une valeur négative indique un regard dans la partie basse de l'écran.

In order to complement this type of representations with statistical inferences, the matrices of values collected with and without assistance were compared. A Wilcoxon signed-ranks test indicated that the assistance and the no assistance conditions significantly differed the one from the other for both the left and the right bend (Left bend:  $Z = 2.32$ ;  $p < .03$ ; Right bend:  $Z = 3.65$ ;  $p < .0003$ ).

### III.3 DYNAMIC AREA OF INTEREST (AOI)

Introduced by the famous work of Land & Lee (1994) showing the importance of the Tangent Point (TP) on steering control, the dynamic area of interest technique offers an analysis of eye movements relative to a dynamic reference on the driving scene rather than on the display screen. This method is time consuming because it is relying on an image per image analysis of the gaze position collected relatively to a dynamic reference on the driving scene. Gaze positions analysis relative to the TP is particularly well suited when focusing on vehicle control. Indeed the TP is known to be particularly useful to steer the car (Land & Lee, 1994). Dynamic area of interest is not limited to the TP and can be defined in relation to a lead vehicle or any visible or invisible object present in the visual scene. Such analysis was performed in order to identify road sections during lane change manoeuvres for instance (Salvucci, Liu, & Boer, 2001; Salvucci & Liu, 2002).

This technique is of particular interest because it offers an analysis of eyes positions relative to the driving environment and is not based on the visual screen as described with the previous methods (gaze plots and AOIs). Following Land and Lee (1994) work, Figure 4 represents four contour plots showing the distribution of gaze positions relative to the tangent point (located at 0 in X-axis and Y-axis) for the left bend (the two top graphs) and the right bend (the two bottom graphs) in the no assistance condition (the two graphs on the left) and in the assistance condition (the two graphs on the right). Four levels of contours are displayed (0.2, 0.4, 0.6, 0.8). The contours are lines relying the points that have the same gaze positions density levels. The outer contour (0.2) for instance is a line relying points with the same proportion of density of gaze positions relative to the maximum density (here 0.2). Descriptively, the areas delimited by the contours appeared to be centred around the TP. These areas also appeared larger in the assistance condition compared with the no assistance condition, with more gaze positions



density on the left and beyond the TP in the left bend, and more gaze positions density on the right and beyond the TP in the right bend (Figure 4).

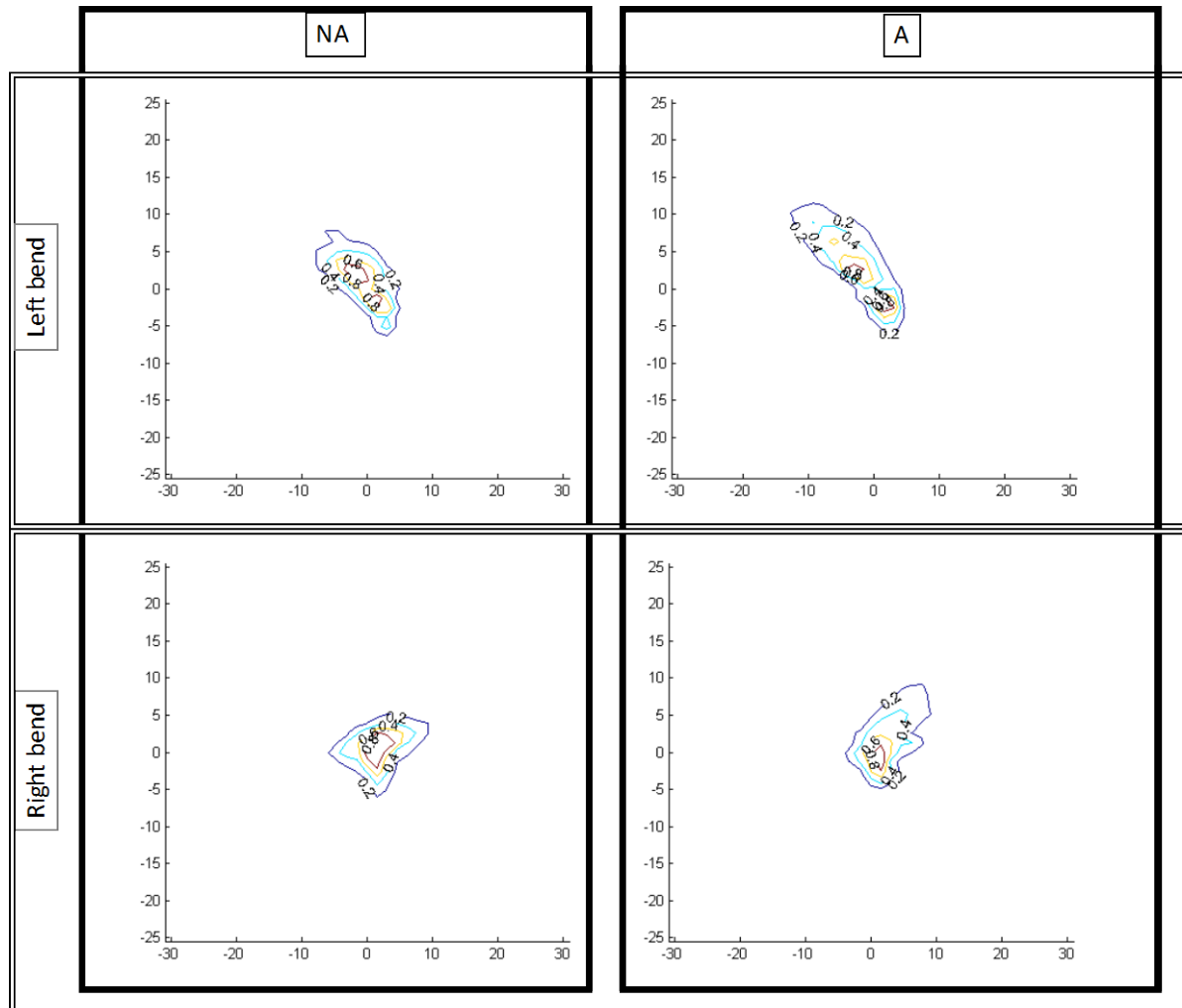


Figure 4: Contour plots representing all gaze positions collected for all participants relative to a dynamic point on the visual screen (i.e. the tangent point). The two top graphs represent the left bend (NA on the left and A on the right). The two bottom graphs represent the right bend (NA on the left and A on the right). All gaze positions are represented in degrees of visual angle relative to the tangent point for the considered bend. 0 on the X axis represents the tangent point on the horizontal dimension, a positive value on the X axis indicates a gaze located on the right of the tangent point and a negative value a gaze on the left of the tangent point. 0 on the Y axis represents the tangent point on the vertical dimension, a positive value on the Y axis indicates a gaze located below the tangent point and a negative value a gaze behind the tangent point. Four levels of contour are represented (0.2, 0.4, 0.6, 0.8).

Figure 3 : Cartes en iso-lignes représentant toutes les positions du regard recueillies pour l'ensemble des participants relativement à un point dynamique de la scène visuelle (i.e. le point tangent). Les deux graphiques situés en haut représentent le virage à gauche (en condition non assistée à gauche et avec un véhicule hautement automatisé à droite). Les deux graphiques

situés en bas représentent le virage à droite (en condition non assistée à gauche et avec un véhicule hautement automatisé à droite). Les positions du regard sont exprimées en degrés dans un repère centré sur le point tangent. 0 sur l'axe des abscisses correspond au point tangent horizontalement, une valeur positive indique un regard à droite du point tangent tandis qu'une valeur négative indique un regard à gauche du point tangent. 0 sur l'axe des ordonnées correspond au point tangent verticalement, une valeur positive indique un regard au delà du point tangent tandis qu'une valeur négative indique un regard en deçà du point tangent. Quatre iso-lignes, correspondant aux fractions de densité des regards par rapport à la densité maximale, 0.2, 0.4, 0.6 et 0.8 sont représentées sur les quatre illustrations.

In order to complement this type of representations with statistical inferences, the percentage of time spent by drivers looking at a region of  $5^\circ$  around the tangent point was computed. This analysis is directly inspired from Land and Lee's work because contour plots are not offering the possibility to perform detailed statistics (Land & Lee, 1994). The percentage of time drivers spent looking at a region of  $5^\circ$  around the tangent point revealed a significant difference between the two conditions for both the left and the right bend (Left bend: NA-A;  $d=58.4\%-31.7\%=26.7\%$ ;  $t(17)=5.97$ ;  $p<.0001$ ; Right bend: NA-A;  $d=61.4\%-37.6\%=23.8\%$ ;  $t(17)=5.82$ ;  $p<.0001$ ; see Fig. 5). With assistance, drivers spent less time looking at the TP area compared to the no assistance condition.

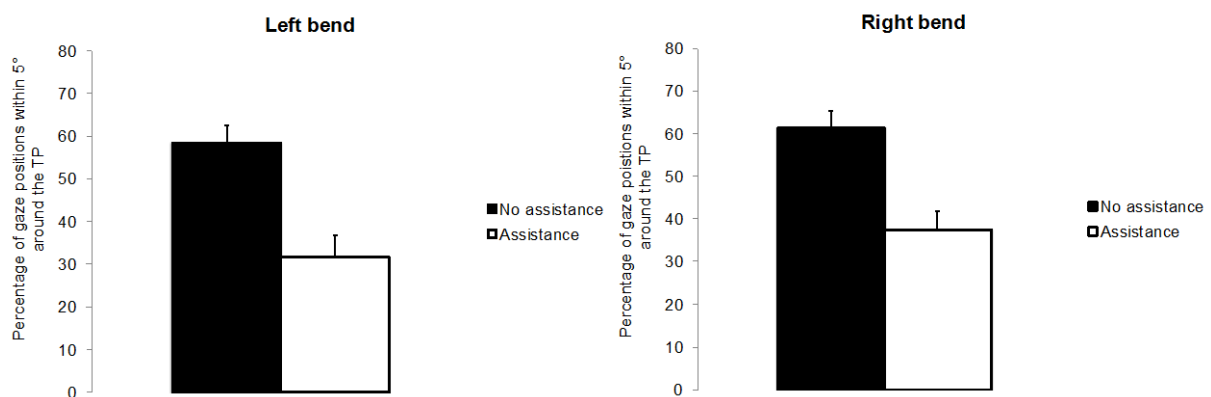


Figure 5: Percentage of gaze positions within  $5^\circ$  around the tangent point in the assistance (A) and no assistance (NA) conditions for left and right bends. The error bars represent one standard error.

Figure 2 : Pourcentage de positions du regard situées dans une zone de  $5^\circ$  autour du point tangent avec assistance (A) et sans assistance (NA) pour le virage à gauche et le virage à droite considéré. Les barres d'erreur représentent l'erreur type.

### III.4 DYNAMIC POINT

The last method that can be used is in line with the previous dynamic AOIs analysis, relative to a dynamic point of the visual scene relevant for explaining the participants' behaviours. Here the tangent point (TP) has been used because of the importance of this particular point while

negotiating bends. Gaze positions proportions are decomposed on X-axis and Y-axis dimensions and by degree of visual angle. The distribution of gaze positions was divided in intervals of 1° of angular deviation from the TP. This procedure was repeated for both vertical (Y-Axis) and horizontal (X-Axis) gaze position components for all participants. All gaze positions that deviated more than 15° from the TP in one direction or the other were grouped in two extreme intervals (gaze positions >15° and <-15°). All gaze positions collected in all drives and for all participants were decomposed in vertical and horizontal components and are presented in the different conditions in Figure 6. The four graphs of Figure 6 are illustrating gaze positions distributions in the assistance and no assistance conditions for the left and right bends on the X-axis and Y-axis dimensions.

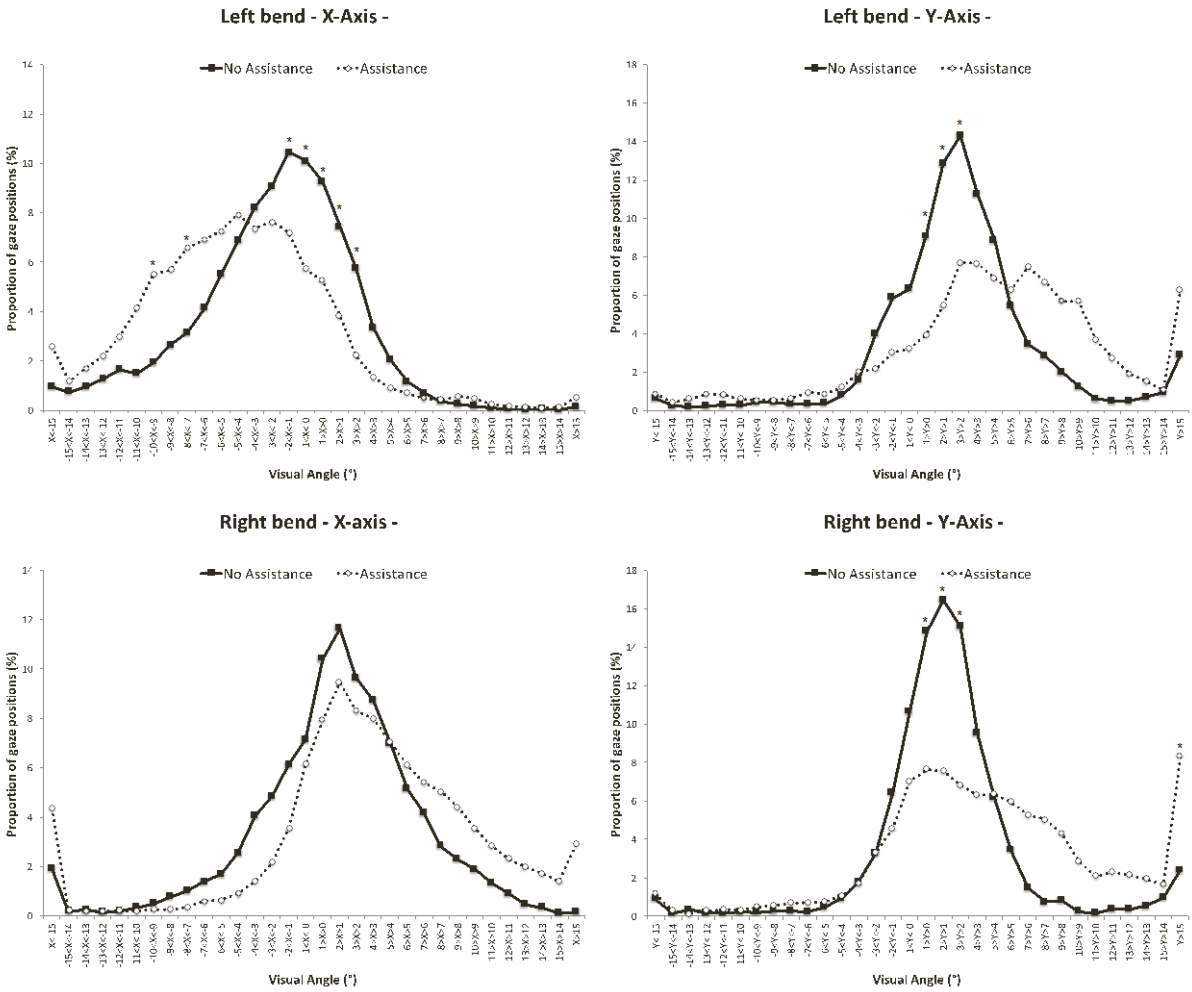


Figure 6: Proportion of gaze positions collected for all participants relative to the tangent point, degree of visual angle by degree of visual angle. The two top graphs represent the left bend. The two bottom graphs represent the right bend. The two graphs on the left represent the X-axis dimension of gaze positions and the two graphs on the the Y-axis dimension of gaze positions. All gaze positions are represented in degrees of visual angle relative to the tangent point for the considered bend. 0 on the X axis represents the tangent point on the horizontal dimension, a positive value on the X axis indicates a gaze located on the right of the tangent

point and a negative value a gaze on the left of the tangent point. 0 on the Y axis represents the tangent point on the vertical dimension, a positive value on the Y axis indicates a gaze located below the tangent point and a negative value a gaze behind the tangent point. The stars indicate a significant difference between the no assistance and assistance conditions for the visual angle considered ( $p < .05$ ).

Figure 6 : Proportions de positions du regard pour l'ensemble des participants dans un repère ayant pour origine le point tangent et avec un échelonnage degré d'angle visuel par degré d'angle visuel. Les deux graphiques situés en haut représentent le virage à gauche et les deux situés en bas représentent le virage à droite. Les deux graphiques situés à gauche représentent les coordonnées en abscisse des positions du regard et les deux graphiques situés à droite les coordonnées en ordonnées de ces mêmes positions du regard. Les positions du regard sont exprimées en degrés dans un repère centré sur le point tangent. 0 sur l'axe des abscisses correspond au point tangent horizontalement, une valeur positive indique un regard à droite du point tangent tandis qu'une valeur négative indique un regard à gauche du point tangent. 0 sur l'axe des ordonnées correspond au point tangent verticalement, une valeur positive indique un regard au delà du point tangent tandis qu'une valeur négative indique un regard en deçà du point tangent. Les étoiles indiquent les degrés d'angle visuel pour lesquels la différence entre les conditions sans assistance et assistée est significative.

In order to complement this type of representations with statistical inferences, 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 variables, were performed on both vertical and horizontal gaze position data. This analysis was run in order to investigate the interaction between the assistance condition and the angular deviation from the tangent point. The results were as follows:

For the left bend proportion of gaze positions on the X-axis: a significant interaction was found between the assistance condition and the horizontal angular deviation from the tangent point ( $F(31,544)=8.98$ ;  $p < .0001$ ). Bonferroni post-hoc analysis indicated a significant difference between the NA and A conditions at seven different angular deviations ( $p < 0.05$ , starred in Figure 6). Compared to NA, drivers gazed less around the TP with assistance redirecting their gaze further left of the TP. For the left bend proportion of gaze positions on the Y-axis: a significant interaction was found between the assistance condition and the horizontal angular deviation from the tangent point ( $F(31,544)=7.37$ ;  $p < .0001$ ). Bonferroni post-hoc analysis indicated a significant difference between the NA and A conditions at three different angular deviations ( $p < 0.05$ , starred in Figure 6). Again, compared to NA, drivers gazed less around the TP with assistance. Gaze positions were insignificantly more numerous further beyond the tangent point with assistance compared to NA.

For the right bend proportion of gaze positions on the X-axis: a significant interaction was found between the assistance condition and the horizontal angular deviation from the tangent point ( $F(31,544)=4.53$ ;  $p<.0001$ ). But post-hoc analysis did not reveal any significant differences between NA and A conditions. Descriptively, all gaze positions were slightly deviated to the right with assistance compared to NA. For the right bend proportion of gaze positions on the Y-axis: a significant interaction was found between the assistance condition and the horizontal angular deviation from the tangent point ( $F(31,544)=12.46$ ;  $p<.0001$ ). Post-hoc analysis indicated a significant difference between the NA and A conditions at four different angular deviations ( $p<0.05$ , starred in Figure 6). As observed for the left bend, compared to the NA condition, drivers gazed less around the TP with assistance. Gaze positions were more numerous further beyond the tangent point with assistance, this was significant for gaze positions over  $15^\circ$ .

#### IV DISCUSSION

First of all, it is important to underline the variety and the number of methods used to analyse gaze positions during car driving. This might be due to (1) the relative novelty of eye-trackers in research laboratories, resulting in the lack of a standard methodology to assess drivers' visual scanning and (2) the variability and complexity of eye movements collected during car driving. Four main gaze positions analysis techniques used in the context of a dynamic car driving environment were identified in the literature. The underlying objective was to compare these techniques in order to identify the most adapted to qualify drivers' visual explorations. Many other techniques and measures were not considered here (see Holmqvist et al., 2011 for a comprehensive description of all methods). They were not considered because not adapted and therefore not used in the context of dynamic environments. The analysis carried out here through the four selected techniques showed an important variability of results depending on the technique considered. Based on the results collected while negotiating bends with a highly automated vehicle or a regular vehicle, it appears that the analysis techniques relative to a dynamic area or point (namely dynamic AOIs and dynamic point) in the visual scene were the best suited for the car driving dynamic environment considered. Therefore, these two methods may be considered as the gold standard methods in the context of driving environments. In the following lines, advantages and drawbacks of each analysis technique will be considered and the impact on safety and human factors assessment discussed.

Considering gaze plots analysis, descriptive conclusions were not clear, even if the gaze positions recorded were not completely similar between the NA and A conditions. For the left bend, gaze position in the A condition seemed located upper on the screen compared to the NA condition. But this observation was not so clear for the right bend. For both bends, more gaze positions were observed on the speedometer area, located at the bottom left of the screen (Figure

1). Statistics revealed a smaller gaze positions variability both horizontally and vertically in the NA condition compared to the A condition, as if drivers concentrated their visual explorations when driving with assistance. Even if significant in the left bend for vertical variability, very little differences between NA and A (within  $1^\circ$  of visual angle) gaze positions variability were observed in the left bend (Figure 2). This difference between bends, although unexpected, may be due to the difference between curvature radii (slightly more important in the right bend), the road section ahead of the bend and the general driving context (e.g. the presence of a wall on the right of the road during a part of the left bend limiting visual explorations) as well. If more precise, AOIs based on the results analysis did not bring more information than gaze plots. Participants looked more on the left of the screen during left bends and more on the right during right bends. Heat maps representing the density of gaze positions did not bring forward any notable differences between NA and A conditions whatever the bend considered, apart from denser gaze positions found in the speedometer area with A for both bends (Figure 3). If global significant differences were found for both bends between NA and A conditions, those differences cannot be clearly located.

Results gained using the dynamic AOI technique are much different and more instructive. Based on contour plots, it is notable that drivers looked at the vicinity of the TP most of the time while negotiating bends (Figure 4). This result replicates previous findings (Kandil et al., 2009; Land & Lee, 1994; Mars, 2008; Wilson et al., 2007). The shape of contours indicates higher gaze positions density to the left of the TP for the left bend and to the right of the TP for the right bend. This trend was present without assistance but is reinforced with highly automated driving. Assistance also expands gaze density behind the TP, as if drivers, relieved from steering control, engaged in a more anticipative visual scanning. This suggests that drivers tend to anticipate future parts of the road by exploring the driving scene even further ahead with highly automated driving. Statistics confirmed that drivers spent significantly less time looking at the TP area in A than in NA condition. These results are confirmed and detailed using the dynamic point technique. For the left bend, assistance introduced a shift in gaze positions behind and to the right of the TP. Whereas in the right bend, assistance introduced a shift in gaze positions behind and to the left of the TP (Figure 6). All things considered, it appears that the results and their interpretation can be strongly influenced by the analysis technique selected. Dynamic area and point in the visual scene techniques appear to be the best suited for the dynamic car driving situation considered.

In the following paragraphs, the advantages and drawbacks of each technique used are discussed. Gaze plots offer a nice and easy preview of eye movements data within the visual screen considered as the frame of reference. These representations are highly understandable because of the familiarity of two-dimensions plots. The understandability of the gaze plots is even improved when a background image is added in order to offer an image of reference. Nevertheless, gaze plots in the context of dynamic car driving come with several drawbacks.

The most important is due to the fact that despite the background image selected to illustrate the driving situation, no real indications on what was actually projected on the screen are available. In addition, in experiments with several participants (here eighteen participants) and with several repetitions (here four drives were run per condition) adding all gaze positions on the same representation is not possible due to the visual overload of the considered representation. Data interpretation might also be misguided by the background image selected. Considering the bottom illustrations of Figure 1 may lead to interpret gaze positions as very close in driving environment, although this is simply induced by the image not corresponding to the actual driving scene. In relatively sharp bends, as those used in the current experiment, most of the virtual road was closer to the driven vehicle than it appears on the selected background image. Statistical inferences are also limited to general analysis such as gaze positions variability because of the lack of references in the dynamic environment.

Areas Of Interest (AOI) offered an additional value to the previously described gaze plots. Using this technique, researchers may define areas of the screen that are of particular interest for them. Elements that remain located at the same position on the screen at all times, as the speedometer in our case, benefit the most of such an analysis. It is easily and accurately possible to analyse the density of visual scanning on the speedometer between in NA and A conditions. Even if this is a specific situation that was not the focus of the current work, it could be noted that drivers looked more at the speedometer with assistance compared to the unassisted condition. Concerning gaze positions in all other parts of the driving scene, this methodology offers the possibility to select or to make emerge AOIs based on the screen as the frame of reference. Both selection and emergence approaches can be useful depending on the study objective. If AOIs are based on the results and not selected by researchers, the analysis is undoubtedly neutral and results are formally more accurate because of the much greater number of AOIs considered. This second option was therefore adopted. In addition to gaze plots, all participants and repetitions are taken into account in the heat maps illustrations. As for gaze plot analysis, the main drawback of this technique is that no real indications on what was actually projected on the screen are available, because the screen and not the driving environment is taken as the frame of reference. Despite the improvement compared to gaze plots, data interpretation remains difficult due to the frame of reference used and the lack of references in the dynamic environment. This technique might be more successful when comparing very different driving situations. Statistical inferences are also limited because carried out on the entire matrix of AOIs.

Dynamic AOIs method best suits the dynamic environment. Descriptively the contour plots centred on a dynamic area offer very convincing results. Here the TP region was selected as the dynamic AOI because of the particular importance of that road section when negotiating bends. The AOI was defined as the 5° of visual angle around the TP. But any object present (i.e. lead vehicle, lane edges, billboards...) or virtual (on simulated environments such as the TP here)

on the driving scene could be used. Contour lines link points with the same gaze positions density. Repeating the procedure for various levels of density led to plot areas where drivers gazed more. Inferential statistics are possible based on the amount of gaze positions located in the AOI considered in the different conditions of the experiment. Here the AOI (i.e. 5° of visual angle around the TP) was gazed less in the A condition than in the NA condition. Using this technique, information on gaze position location on the screen is lost, but without any negative consequences. However, this technique suffers from two drawbacks. The first is that researchers need to define the AOI(s) for the considered experiment. If the AOI was relatively obvious in the current work, this may not always be the case. The second is related to technical difficulties to record a dynamic AOI (if possible) or the time required to analyse image per image the eye-tracking videos relatively to a dynamic AOI. The dynamic point technique is directly in line with the dynamic AOI one and presents the same advantages and drawbacks, apart that it offers a more detailed description of gaze positions in the driving scene, because it is relative to a point, and not to an area.

Many studies tend to avoid the difficulty of analysing eye movements during car driving by limiting the eye-tracker use to visual areas that remain at the same location on the screen at all times such as in-vehicle information systems. Total glance duration, frequency and single glance duration are the most common measures used to do so (ISO 15007-2. Road vehicles, n.d.). This approach is fully effective as far as the information displayed on that part of the visual scene is not changing over time, such as a speedometer that constantly indicates the vehicle speed. The approach is only partly effective when the areas considered are fixed on the screen but displaying dynamic moving images, for example the vehicle mirrors. In that case it is of interest to count the number of glances to the mirrors for instance but the problem of not knowing what drivers are looking at in the mirrors remains. In sum, the issue of eye movements analysis in dynamic environments may be partly solved focusing only on fixed areas, but using dynamic AOIs or dynamic points offers a more complete analysis alternative.

As stressed previously, the results appeared to be different depending on the analysis technique used. Differences in gaze positions between the NA and A conditions were not shown accurately using gaze plots or AOI analysis based on the visual screen. Only the dynamic AOI and the dynamic point analysis pointed out visual scanning differences between the NA and A conditions. Therefore, the selection of the most appropriate technique is a key element in eye movements interpretation. This is of particular importance when it comes to safety in car driving. In the current example, drivers' visual disengagement from the TP region is critical because looking at that region is a key contributing factor to steer the vehicle efficiently (Wilson et al., 2007). Not being able to stress these changes in visual scanning behaviours could lead to ineffective assistance design, considering for instance that gaze behaviours are not critically impacted while driving a highly automated vehicle. Difficulties were observed when drivers had to return to manual control while driving with highly automated vehicle (Hoc et al., 2006).



Not using a visual scanning analysis technique based on dynamic area or point would lead to consider that difficulties drivers face when returning to manual control are not due, at least partly, to changes in visual scanning of the driving environment

Although dynamic AOI and dynamic point techniques are allowing an accurate interpretation of eye movement data in dynamic environments, some limitations must be considered in the interpretation. The driving context is a key element that clearly impacts the visual scanning of the driving scene. Drivers' behaviours are different with traffic and without for instance. Generally speaking, complex driving environments offer more opportunities for drivers to explore the driving scene. Eye movements were recorded here in relatively simple and flat road edges environments but the results might be affected by more complex driving backgrounds. In addition, even if it is possible to multiply dynamic AOIs and dynamic points, the results might be harder to understand with several dynamic elements of the driving scene. Another limitation is directly linked to the use of eye-tracking. Only central vision is considered and no information on peripheral vision is recorded, although it is known that drivers use peripheral vision (Mourant & Rockwell, 1970; Summala et al., 1996). As a consequence, even if parts of the driving scene are not gazed directly, they may be of importance to complete the driving task and not taken into account based on gaze positions analysis. Despite these general limitations, any dynamic situation, including all virtual reality environments, could benefit from analysis based on a dynamic reference on the visual scene. These techniques could particularly benefit to cognitive ergonomics where dynamic situations are often under the scope of analysis (Hoc, Amalberti, Cellier, & Grosjean, 2004).

### **Acknowledgments**

This work was performed within the framework of the LABEX CORTEX (ANR-11-LABX-0042) of Université de Lyon, within the program "Investissements d'Avenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR).

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