Using Virtual Reality Techniques to Study Cognitive Processes in Car Driving Activity

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Abstract: A central question in cognitive sciences is how behaviors adapted to the situations encountered are produced. This question can be addressed in different ways and often requires the researcher to choose between highly controlled and standardized laboratory situations (commonly referred to as artificial settings) and studies undertaken in natural settings which may be more realistic, but cannot be controlled as required by a rigorous scientific approach. Using car driving as an example, our study will show how virtual reality (VR) offers a compromise between these two alternatives. Indeed, VR can simulate controlled immersive environments that offer different levels of realism. Moreover, VR makes it possible to implement different devices. For instance, VR enables researchers to analyze oculomotor behavior, which is fundamental in the field of car driving and is considered an indicator of attentional deployment. The work presented in this paper is based on a car driving simulator currently under development and aimed at studying the cognitive processes involved in car driving such as attentional processes and anticipatory mechanisms.

1 INTRODUCTION

A central question in cognitive sciences is how behaviors adapted to the situations encountered are produced. This question is not as trivial as it seems because producing relevant behavioral reactions requires the mobilization of complex cognitive processes. Car driving thus lies at the heart of numerous researchers concerns and is perceived, in particular, as an ≪ integrated multi-task behavior engaging several processes and requiring different interrelated skills that rely on interconnected visual, motor, and cognitive brain systems ≫ (Graydon et al., 2004). One of the difficulties commonly encountered is the need to choose between highly controlled laboratory situations and studies undertaken in natural settings. While the former confers a more or less artificial character on the situations, the latter, which is more realistic, does not enable researchers to control all the parameters of the situations that are expected to be standardized.

The situations created in laboratories are generally defined by their artificial nature. Indeed, the situations presented to participants sometimes greatly differ from the situations encountered in natural settings. To address this problem, some researchers have focused on presenting driving situations that are as ecological as possible; i.e., situations presenting natural scenes depicting either static driving scenes (i.e., photographs, e.g., (Galpin et al., 2009) or dynamic video clips of driving (Crundall et al., 2003)). In addition to presenting stimuli closer to natural driving conditions, this choice is largely driven by the need to present strictly identical situations for all participants. Indeed, without this condition, participants performances cannot be compared and the validity of the research studies is likely to be prejudiced.

As engaging as it might seem, this mode of working has its limitations because the researcher depends on the characteristics of the environment and events occurring during the capture of movies or still images. A second limitation is that the subject cannot act on the environment (even if the researcher is careful to present situations as close as possible to natural driving by asking, for instance, the subject to follow the road by turning a steering wheel), while car driving mobilizes both perceptual and action-related knowledge (Blättler et al., 2012). This highlights the necessity for devices that allow subjects to interact with the environment in order to be closer to natural driving

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conditions. An alternative approach to highly controlled experimental situations involves undertaking studies in natural settings. This approach has been used by Underwood et al. (2003), who observed the behavior of car drivers in natural driving situations.

While studies in natural settings present high ecological validity, their greatest shortcoming is that they do not allow researchers to control the environment in which the subject is driving (i.e., the different events that occur despite participants being presented with a similar path, or the impossibility of predicting traffic conditions, as in the case of Underwood et al. (2003)), a necessary condition for acceptable validity. As a result, the situations differ from participant to participant and are more difficult to compare.

The development of virtual environments (VEs) has made possible a compromise between natural and experimentally controlled situations. Indeed, Virtual Reality (VR) simulations allow researchers to control the complexity of the presented environment (e.g., in terms of perceptive richness, with, for instance, the addition or withdrawal of visual details such as the presence of traffic signs) or occurring events (e.g., presence or absence of distractors such as vehicles or pedestrians, or events such as car accidents) (Rizzo, 2002). Moreover, VR makes it possible to implement different devices (Bian et al., 2013; Bian et al., 2015; Zhang et al., 2015; Lei et al., 2016). For instance, VR enables researchers to analyze oculomotor behavior which is fundamental in the field of car driving and is considered an indicator of attentional deployment. Finaly, the relevance of such an approach depends on the presentation of situations that are highly controlled and strictly identical across participants, as well as the fact that the approach accords the encountered situations a more ecological nature by offering, in particular, the possibility of interacting in real time with the environment in which the subject may be immersed.

The objective of this paper is to present a car driving simulator currently under development and aimed at studying the cognitive processes involved in car driving such as attentional processes and anticipatory mechanisms. In the next Section, we describe some existing driving simulators that have been developed so far and present some related works about visual attention and eye-movements in driving, load theory of attention, cognitive control and anticipatory mechanisms. Section 3 presents the VEs we have developed and our driving simulations. In Section 4, we focus on the measure and analysis of collected eye-movements. In Section 5, we present our approach to investigate cognitive processes such as anticipatory mechanisms in driving simulation. Finally, we will present our conclusions and suggest avenues for further work.

2 RELATED WORK

2.1 Driving Simulators

Nowadays, two types of driving simulators are available : (1) static simulators, with which the user experiences no acceleration or forces and (2) dynamic simulators, which are based on motion platforms. The most advanced static simulators incorporate a fully instrumented vehicle placed in front of a semi-cylindrical or multi-screen display. Among these systems, we can cite the SIM2 simulator from the French Institute for Sciences and Technologies of Transport, Development and Networks (IFSTTAR). This simulator incorporates a Citroën Xantia placed in front of a three-sided screen (Auberlet et al., 2010). There is also the Fraunhofer IAO simulator, consisting of a Renault Scenic placed in front of a three-sided screen, with a 180-degree field of view. Note that this simulator offers two screens behind the vehicle (Marberger, 2008). The simulator developed at the University of Leeds consists of a Rover 216 and a curved screen with a 120-degree field of view (Blana and Golias, 2002).

Most dynamic simulators integrate acceleration feedback via the use of a motion platform. We can cite for example the SHERPA simulator from PSA Peugeot-Citroën, which was duplicated at the LAMIH Laboratory at the University of Valenciennes. This simulator, consisting of a Peugeot 206 mounted on a Rexroth Hydraudyne platform, uses a three-sided screen with a 180-degree field of view (Younsi et al., 2009). In the same category, the VERA simulator of the Technology Environment Safety Transport Laboratory of the University of Naples consists of one half of a C2 Citroën, mounted on a six-stage platform of freedom. This vehicle is placed in front of a screen made up of three faces and has also a 180-degree field of view. LCD screens in the central and exterior mirrors provide rearward vision (Torrieri et al., 2008). The CARRS-Q (Center for Accident and Road Safety) Advanced Simulator at the University of Queensland consists of a vehicle placed on a Rexroth platform. The simulator is equipped with a three-sided screen with a 18-degree field of view. LCD screens are placed in both the center and exterior mirrors to provide rearward vision (Haines, 2011). Dynamic simulators also include the KMUDS-4 from Kookmin University in Korea. This simulator consists of a vehicle, a three-sided frontal screen with a

140-degree field of view. The system also has a rear screen with a 50-degree field of view. The restitution of movements is carried out by four motors located under the vehicle (Lee et al., 2007). The Ford VIRTTEX simulator uses a vehicle in a dome containing a cylindrical screen with a 180-degree field of view and a rear cylindrical screen with a 120-degree field of view (Artz et al., 2001). The system is mounted on a platform with six degrees of freedom. In order to reproduce large-amplitude displacements in one or two dimensions, the dynamic simulators can be placed on rails. One-dimensional systems include the MARS simulator of the IFAS (Institut für Fahrzeugtechnik und Antriebssystemtechnik, Germany). The rail used allows a lateral displacement of 1.5 m (Breidenbach and Tomaske, 2004). There is also the simulator III of the National Institute for Road and Transport Research in Sweden. The rail used allows a displacement of 7.5 m. Moreover, the cab can be oriented by 90 degrees, making it possible to reproduce longitudinal and lateral movements (Nordmark et al., 2004). The Daimler simulator consists of a dome containing a vehicle and a 360 degrees cylindrical screen, mounted on a platform with six degrees of freedom. The system uses a rail with an amplitude of movement of 12 m (Zeeb, 2010). The Cards 2 simulator developed by Renault, also falls into this category. It is composed of a cabin equipped with a dashboard of a Mégane, integrating a manual gearbox with five ratios. Three screens with a horizontal viewing angle of 150 degrees and a vertical 40-degree field of view are used. Two LCD screens are placed in the exterior mirrors, and the image of the central mirror is projected onto the top of the center screen. The simulator is mounted on a platform with six degrees of freedom, allowing a displacement of ± 20 cm and a rotation of ± 20 degrees (Reymond and Kemeny, 2000). Renault has also developed the Ultimate Dynamic Simulator which consists of a cabin equipped with a Laguna dashboard. The steering wheel is equipped with an active feedback system, while the pedals and shift lever are equipped with a passive feedback system. The images are projected onto a cylindrical screen having a horizontal 150-degree field of view and a vertical 40-degree field of view. The NADS-1 simulator from the University of Iowa has 19.5 m longitudinal and lateral displacements (Greenberg et al., 2006). Note that the cabin incorporates a 360 degrees cylindrical screen.

Some dynamic simulators are based on a specific architecture for the simulation of movements and accelerations. For example, the CyberMotion simulator from the Max Planck Institute, uses a robot with six degrees of freedom, on which the driver's position and screen are positioned (Grabe et al., 2010). In the same category, there is the Desdemona simulator of the TNO (Mayrhofer et al., 2009).

2.2 Visual Attention and Eye-movements

Vision is the major sense used during the driving activity (Sivak, 1996). The Human Visual System (HVS) is able to resolve fine details in a scene, as well as in a moving sequence, at close and far distances (Snowden et al., 2006). Over the last two decades, HVS which lies at the heart of transportation studies has focused on analyzing visual attention and gaze tracking (Jacob, 1991; Lemonnier et al., 2014; Lemonnier et al., 2015). In this context, the transport field has benefited from recent progress in eye-tracker devices and from the emergence of computational models of visual attention and a new research area, i.e., VR.

Although eye tracking technology is susceptible to data quality issues (Ahlstrom et al., 2012), eye movements have been widely studied in the context of driver behavior, attention management, and to assess task related visual demand (Wierwille., 1993; Mori et al., 2013; Sodhi et al., 2002; Aoki et al., 2010). While many eye movement measures are available today (Holmqvist et al., 2011), some are easier to calculate than others. The most common eye movement events are fixation and saccade. Fixation corresponds to the period of time the eye remains nearly still and a saccade is the rapid motion of the eye from one fixation to another. Analyzing fixation events is especially interesting in driving studies because it is widely accepted that individuals are blind during a saccade. To identify the information that draws the drivers attention outside the vehicle (e.g. traffic signs, signals, pavement markings), the prime measures are those that determine whether the driver is looking at a particular location or signal referred to as Area of Interest (AOI). Several characteristics of eye movements such as eye blinks, pupil dilation and saccadic peak velocity reflect variations in attention, emotion and mental workload over time.

2.3 Load Theory of Attention and Cognitive Control

The ability to focus attention on the elements of environment to be treated in priority and ignore distractions is essential to the production of adapted behaviors. However, this blindness to distractors might be damaging in some situations, as in the case of car driving where it is vital to detect the presence of other vehicles and traffic signs (Lavie, 2010, for a review). The ability to detect distractors during the execution of a task requiring attention can be explained by Lavies load theory of attention and cognitive control (Lavie et al., 2004; Lavie and Fockert, 2005; Lavie, 2010). This theory tends to resolve the debate relative to the locus of attentional selection (early, late) by introducing the idea that focused attention in the face of distractions depends both on the amount and type of information load involved by the task. The load theory posits that focused attention is enhanced under conditions of high perceptual load and degraded in situations involving high load on cognitive control processes (e.g., working memory). Indeed, tasks involving high perceptual load consume the overall processing capacity, leaving no more resources available for the perception of irrelevant distractors. Such a prediction is in agreement with the view of early attentional selection, according to which the individuals perceive only the objects to which they pay attention because of limited perceptual processing capacity. Conversely, in the case of tasks involving a low perceptual load, the processing capacity is not totally used, allowing the processing of distractive information. This second prediction is in agreement with the theory of late selection that postulates that perception refers to an unlimited capacity automatic process. In this case, the efficiency of attentional selection, which refers to "the extent to which distractors that have been perceived can be prevented from gaining control over behavior" (Lavie, 2010, p. 143), depends on the load on cognitive control processes, a high working memory load being for instance the origin of increased interference of distractors.

2.4 Anticipatory Mechanisms

Anticipatory mechanisms involved in the perception of the surrounding world is at the heart of the production of adaptive behavior (Blättler et al., 2012), for instance in the case of car driving. Thus, the ability to realize predictions concerns both the likely future trajectory of a moving object or the likely evolution of the dynamic environment in which the observer is embedded, a phenomenon known as representational momentum (Freyd and Finke, 1984) and the prediction of areas of the environment just outside the observers visual field. This phenomenon is known as boundary extension (Intraub and Richardson, 1989) and is described as the tendency to overestimate the spatial expanse of a previously perceived scene, the visual system inferring information that could be present just beyond the boundaries of a view. As a result, the observers memory includes extended boundaries in comparison to the boundaries of the original scene. While this phenomenon is generally described as a memory error, it presents an important adaptive value by facilitating the interactions with the environment through, for instance, tasks such as navigation (Hale et al., 2016).

Several studies have shown that car driving expertise modulates boundary extension (Ménétrier and Didierjean, 2013), with experts processing the scenes belonging to their expertise field more effectively than novices (Reingold et al., 2001; Mourant and Rockwell, 1972). However, one of the limitations of these studies is that they relied on the presentation of road-scene photographs passively grasped by observers, whereas car driving implies perceptivo-motor representations and abilities (Blättler et al., 2012).

3 VIRTUAL ENVIRONMENTS AND DRIVING SIMULATION

3.1 Virtual Environments

Two complementary VEs have been developed for the study of cognitive processes (attentional and prediction) and the perceptual mechanisms involved when one is driving a vehicle. The first is an urban environment (Fig. 1) composed of buildings arranged along linear axes and intersections with traffic signs and traffic lights. Restaurants and cafés were modeled and placed in the streets. Each intersection can be set according to each experiments needs. The traffic lights therefore behave realistically and are fully controlled using finite state machines. As shown in Figure 1, below, a pavement marker is also present (white and yellow lines on the ground). Vehicles and characters with realistic autonomous behaviors can also be placed in the environment. Artificial lights for illuminating the streets and the buildings are also present. To increase the realism of the simulation, vegetation was integrated (bushes and trees). These elements can be animated in real time according to weather conditions (air stream).

Lastly, the VE offers a more or less rich soundscape. Depending on the traffic, different audio clips can be played. By default, the noise generated by the car engine and the braking is present in the simulation even though, naturally, it can be cut off. It is worth noting that sound information increases the realism of the simulation but is also perceived as an important driving aid. The Figure 2, provides a view of the countryside VE during the driving simulation. This VE comprises open fields and has minimal vegetation. During the simulation, however, the driver may pass through small villages comprising farms and some

Figure 1: A user's view of the virtual city during the driving simulation.

Figure 2: A user's view of the countryside VE during the driving simulation.

houses. The driver might also pass through a forest with many trees.

3.2 Driving Simulation

Two driving approaches are proposed: (1) free driving in which the driver operates the vehicle and has full dynamic control of simulation parameters (steering, speed, etc.) and (2) constrained driving in which the driver has only partial control of the vehicles behavior. In the latter case, the vehicle advances on rails (Fig. 3) and its speed is kept constant. The driver controls when the vehicle starts and when it stops. This second approach was implemented in order to ensure that all subjects had the same visual stimuli. With regard to our experiment, we chose to represent neither the inside (virtual camera positioned in front of the steering wheel) nor the hood of the vehicle, especially when the user had two wheels in front of him/her (a physical one and the virtual one) during the driving simulation.

Our experimental platform is based on a simple configuration (Fig. 4) and provides haptic feedback using the Logitech G27 steering wheel. This device has the following characteristics: (1) a powerful dual-motor force feedback mechanism with helical gearing, (2) a lever for six-speed engagement of reverse gear with pressure, (3) the ability to change speed/tachometer (4) a leather coated wheel with a diameter measuring 28 cm and (5) an accelerator pedal, steel brake and clutch.

Figure 3: Example of rails used to constraint the car path.

Figure 4: Experimental platform for driving simulation and eye-tracking.

4 MEASURE AND ANALYSIS OF EYE-MOVEMENTS

Twenty four (24) participants took part in a driving simulation experiment based on the driving simulator previously described. The VEs were projected on a screen 55 cm high and 107 cm wide. Participants were positionned approximately 170 cm from the screen, which was placed at a horizontal angle of view of 35° and a vertical angle of view of 18°. A RED eye-tracking system from SMI, running at 60 Hz, was used (see Figure 4). The experiment lasted approximately 30 minutes (ten minutes of free training, ten minutes in the rural environment and ten minutes in the urban environment). Eye movements were first analyzed using the gaze standard deviation. We posited that the standard deviation would reflect mental workload and would depend on the environment (rural/urban) (Burnham et al., 2014). The horizontal standard deviation for the rural environment was 3.4° and the vertical deviation was 3.5°. These weak values can be explained through the monotonous environment along the route and the drivers concentration on his/her trajectory alone, i.e., concentration on the vanishing point. Sample of eye-movement paths and hot spots during the exploration of the virtual city are given in Figures 5 and 6 respectively.

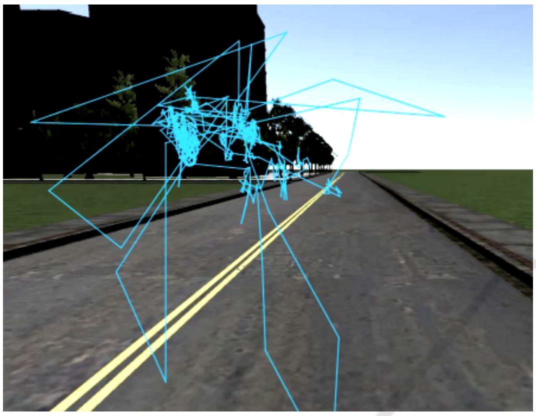

Figure 5: Eye-movement paths during the exploration of the virtual city.

For the urban environment, the horizontal standard deviation was 7.0° and the vertical deviation was 3.0°. The vertical/horizontal difference can be explained through the perspective projection of the world; while the vertical dimension represents the perspective, the horizontal dimension is related to a fixed distance. Gaze exploration (looking at cars, traffic lights, etc.) leads to greater eye movement in a horizontal direction. Scene complexity also increased the standard deviation. After these findings, we turned our interest to the utility/distracter ratio (on the road) and the AOI approach, which requires us to detect the road in every frame and compare this with the eye position. To this end, a robust image processing algorithm should be implemented and applied to each frame of the acquisition movies. These studies are currently under development will be presented in a future paper.

5 ANTICIPATORY MECANISMS IN DRIVING SIMULATION

In addition to the creation of situations closer to those encountered in natural settings, VR enables to implement experimental tasks aimed at studying specific cognitive processes. One of the goals we pursued here is the study of the anticipatory mechanisms involved in the perception of the surrounding world. In this context, the use of VR will enable us to study this question by proposing a driving task to novice and expert car drivers, during which they will move in the virtual city either as drivers (i.e., involved in the driving action condition) or as passengers (i.e., less involved condition).

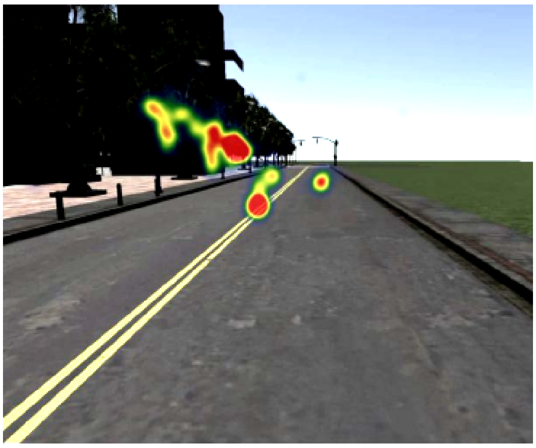

Figure 6: Hot spots during the exploration of the virtual city.

To study anticipatory mechanisms in driving, a boundary extension task will be incorporated at different times: during driving, the scene will be frozen for a very brief duration (250 ms) before being replaced by a black screen (1 s). Immediately afterwards, the frozen scene will reappear, but the distance at which it is presented will have been modified. The task of the subject will be to indicate whether the second scene is closer-up, further away, or at the same distance as the original. In order to present comparable situations from one participant to another (i.e., strictly identical scenes), we will use the rail that has been implemented in order to standardize subjects paths and viewpoints. This task will enable us to better understand the simultaneous effects of expertise and involvement in the action on boundary extension and will also enable the immersion of the participants. This appears to be a fundamental question because, in real life, human beings are embedded in environments in which they act toward goals.

6 CONCLUSION AND FUTURE WORK

We have presented a car driving simulator aimed at studying the cognitive processes involved in car driving such as attentional processes and anticipatory mechanisms. To this aim, specific experimental tasks have been developped. The proposed experimental platform is equipped with an eye-tracking system to collect specific eye movement data. Despite the gap between the real and the virtual world, VR is an interesting compromise between highly controlled experimental situations and studies undertaken in a natural setting. Indeed, VR makes it possible to associate a controlled study of cognitive processes with situations closer to everyday life by enabling an interaction with the environment. In future, we plan to add more sensors to get additional data such as physiological data (EMG, ECG, and GSR) for a more in-depth analysis of users behavior and performance.

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