Displays 52 (2018) 30–39

Contents lists available at ScienceDirect

Displays

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

High Dynamic Range Displays improve the realism of motion cues in night driving simulators☆

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ARTICLE INFO

Keywords:
HDR display
Motion perception
Driving simulation
Night-time rendering

ABSTRACT

Night driving is challenging for driving simulations. At night, the constraints on Computer Graphics performance are unusually strong, as many relevant details have low contrasts and low luminance values, while the overall contrast is very high, due to light sources from road lighting and vehicle headlamps. Some level of realism is needed in terms of contrast rendering, because contrast impacts visibility and motion perception, which in turn impact the driving behavior. This is usually achieved in Computer Graphics with Tone Mapping Operators (TMOs), in order to display the computed images on a standard, Low Dynamic Range (LDR) display device. We explore in this paper the drawbacks of these operators for nighttime driving simulations, focusing on motion cues, and discuss the potential benefit of the emerging technology of High Dynamic Range (HDR) display devices.

We have focused on a night-time road environment with an incoming motorcycle. Two experiments have been conducted, with 33 participants. Time-to-Collision (TTC) was considered as a proxy for motion perception. TTC estimations were collected on a HDR display and compared to degraded visual environments. The first experiment shows that the visibility of the motorcycle's outline is the main visual cue for the TTC estimation in nighttime conditions (but this doesn't happen with cars). It suggests that the main drawbacks of TMOs with respect to TTC estimation involves the mapping of low contrasts, which either enhances or impairs the motorcycle visibility. The second experiment explores this hypothesis and shows that enhancing the visibility of the motorcycle leads to biases in the TTC estimation, whereas removing it does not impact the TTC estimation — at the cost of other realism problems. These results suggest that motion cues at night are more realistic with a HDR Display, and that such display devices may be useful in situations where a realistic perception of hardly visible contrasts is needed.

1. Introduction

1.1. High Dynamic Range Displays

In Computer Graphics, most High Dynamic Range (HDR) images are computed using physically-based rendering algorithms [56]. HDR display devices have been designed in order to display the luminance and contrast ranges of these images [62], but as of today, they are very uncommon, and conventional Low Dynamic Range (LDR) display devices are still broadly used. Tone Mapping Operators (TMOs) are needed in order to map the luminance range of HDR images into the available luminance range of those LDR displays [59]. TMOs also need to squeeze the HDR video format into the 8-bit per channel format of the standard video pipeline.

TMOs are designed to cope with a number of constraints in order to provide a pleasant visual experience to the viewer. Each of these operators makes some tradeoff, selecting some visual cues as the most important to be preserved in the displayed image. For instance, one may wish to keep visual appearance cues, such as brightness and details or preserve object detection performance. But an optimal operator eventually depends on the input images, on the preferred visual features, and on the application.

In the following, we explore some problems experienced with the current LDR technology for driving simulators, and discuss the potential benefits of the emerging HDR technology. Because night driving is the most challenging environment for driving simulations in terms of rendering, we explore the drawbacks of LDR displays in night driving. At night, the visual signal is depleted, which is known to alter the estimation of motion cues. More specifically, we use the Time-To-Collision estimate (TTC, see below) as a proxy for motion perception. A poor

☆ This paper was recommended for publication by Richard H.Y. So.

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https://doi.org/10.1016/j.displa.2018.02.006
Received 29 November 2017; Received in revised form 20 February 2018; Accepted 23 February 2018
Available online 08 March 2018

display of contrasts, adaptation luminance and glare is expected to modify the night-time visual performance, making the TTC estimate on a LDR display device closer to daytime TTC estimates than to nighttime estimates.

1.2. Driving simulation

Driving simulators has a major contribution to transportation research. Their ability to study the driver's behavior in safe, controlled and reproducible conditions led to a broad use of these tools in behavioral driving studies, including for the design and assessment of vehicular technology (vehicular design, Advanced Driving Assistance Systems, and at night, automotive lighting systems) and road engineering (and at night, road lighting) [63].

In these studies, a behavioral realism is needed: the driving behavior in the simulator should be as close as possible to the behavior on the road. To achieve this behavioral realism, one should provide the right perceptual cues to the driver at the right time; this includes, above all, visual cues [64].

What does "realism" mean in Computer Graphics? A proposal from James Ferwerda was to describe three levels of visual realism: physical realism refers to displaying the same physical stimulus (e.g. luminance, color) as in the real environment; perceptual realism (photo-realism) refers to providing the same perceptual experience; and functional (semantic) realism refers to providing the same information [27]. In many driving situations, such as in daylight with clear visibility, achieving perceptual realism is easy for a TMO, because most of these operators would keep a high visibility for all relevant objects. But in environments with low visibility, such as in fog and at night, perceptual realism is uneasy to achieve, and in the same time strongly needed, because in these environments perceptual realism is a key for behavioral realism [14]. At night, unfortunately, the constraints on the TMO are unusually strong, as many relevant details have low contrasts and low luminance values, while the overall contrast is very high, due to light sources from road lighting and vehicles headlamps. Thus, for a TMO, perceptual realism is more difficult to achieve at night.

What are the most important visual cues in a driving simulator? Driving includes a number of subtasks (car following, lane keeping, hazard detection, overtaking, etc.), and each of them needs specific visual cues to be achieved properly [5,49]. In terms of Computer Graphics, providing these visual cues with high fidelity depends on various properties of the display system. A short overview of these visual cues is needed here, to understand what kind of driving performance may be impacted by a TMO — especially at night.

- With respect to vehicle control, the main visual cues are given by the roadside, and when available, by the road markings [43,44]. These cues should have the same visibility in Virtual Reality (VR) as on the road, which means at night that their visibility should result from the simulated vehicle headlamps — and possibly from simulated road lighting. When following another car, speed control calls for an accurate perception of the speed and distance of the vehicle ahead.
- Driving includes a number of micro-decisions, such as crossing an intersection and overtaking, involving specific visual cues. The reading distance of road signs should be consistent with the real reading distance (this is a true challenge in terms of display resolution [71]),[1] and the other vehicle's speed and distance need to be accurately estimated. At night, the degraded visual cues need to be degraded as well in a simulator [12].
- Hazard detection refers to the anticipation of potential collisions with other vehicles, pedestrians, barriers, etc. A potential obstacle should be detected at the right time in the virtual environment, and its speed should be estimated with the same bias in VR as on the road.

A TMO may impact some of these visual cues, not all of them. Some cues depend on the maximum visual acuity afforded by the display, that is, on the pixels angular size. For instance, the ability to read road signs, or to discriminate between a pedestrian and a bicycle far away, calls for a good spatial resolution of the display. The same goes for road markings, which may also disappear from the display due to anti-aliasing.

LDR displays cannot reach the dark luminance levels of nighttime road environments. Any TMO would change the visual adaptation [28], as well as the contrast of objects in the scene. This may impact two series of visual cues needed for driving: visibility and motion perception. Visibility depends on an object's contrast with its background, as well as on its size, and on visual adaptation [7,1]. In driving simulations, the visibility should be neither enhanced nor attenuated. Some TMOs have been designed to maintain the visibility of objects [74,33,37], but they cannot succeed continuously for all objects in environments with very high overall contrast, such as a road at night with glare.

In contrast with these visibility-based approaches, motion perception has not been addressed in previous research on rendering in VR. The estimation of the speed and distance of other drivers, which is mainly grounded on motion perception skills, is however a key issue for driving simulation. This is why, in the following, we focus on these motion cues.

1.3. Motion cues in driving

In the context of driving, motion perception may refer either to the perception of self motion, or to the perception of the other cars' and pedestrians' motion. In a driving simulator, self motion perception mainly depends on the motion platform and on peripheral vision [42], but it is also known that low contrasts lead to an under-estimation of one's speed [65], and that low luminance values in the field of view lead to lower driving speeds [58].

The perception of other mobiles' speed is also modified in low contrast environments [69]. At low speed, low contrast objects appear to move slower than high contrast objects [67,9], while they appear to move faster at high speeds [9,70]. Moreover, their motion is perceived differently with rods (in scotopic vision) and cones (photopic vision) [30,77]. Night driving is in the mesopic range, where both rods and cones are active.

Despite the limited understanding of the physiological and psychological mechanisms mediating speed perception, it is clear that luminance and contrast both impact motion perception, and that this perception is more biased when the visual cues are poor, such as in fog and at night [65]. In realistic virtual environments, such biases must also be experienced if one wishes to reach behavioral realism. With this respect, a better understanding of the behavioral consequences of the display technology is needed: LDR displays bias the perception, which impacts the driving behavior. Visibility has previously been considered for its impact on object detection, we shall explore its impact on motion perception.

Among the various indexes related to speed perception, the time-to-contact has been proposed as the main visual cue which allows animals (including humans) to estimate the relative motion of objects [45]. In the context of driving, this visual cue is termed Time-To-Collision (TTC). It is involved in the estimation of other drivers' motion [34,19]. Considering an object moving toward a driver at constant speed, the TTC is technically defined as the time until a collision occurs.

An accurate estimation of the TTC is needed for safe driving, but misperception of the TTC have been found in some important driving situations, such as left turns [19], especially when a motorcycle is involved [52,20]. Importantly, the motorcycles' speed tend to be under-estimated [51], especially at night [17,32]. More specifically, at night,

[1] With respect to route following, the main issue is to read direction signs; the requirements in terms of image rendering are the same as for other road signs.