Preferred Speed of Visual Adaptation to Darkness in Computer Games

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Abstract

The human visual system has the ability to adapt to various lighting conditions. Models of this visual adaptation process are applied to increase the attractiveness of graphics while playing computer games. The main goal of this work is to implement the light adaptation process in a test game framework and evaluate the perceptual impact of adaptation to darkness on the gameplay. We take care of the reliability and physical correctness of the simulation but also artificially modify the adaptation speed to test the player's preferences. The results reveal that faster visual adaptation to darkness is more preferable than an approach which follows the natural behaviour of the human visual system.

Keywords: visual adaptation, adaptation to darkness, visual adaptation in computer games, perception, tone mapping, real time rendering

1 Introduction

Lighting conditions vary significantly depending on the environment in which we are located so a mechanism, which allows the humans to see objects in both bright and dark conditions is indispensable to survival. This process within the human visual system (HVS) is called *visual adaptation* - it allows HVS to adjust to various light conditions ranging from very dark scenes lit by the stars to bright environments illuminated by millions of candelas.

The main focus of this work is *adaptation to darkness*. This is the process which takes place when we switch from well lit environment to a darker one. The adaptation to darkness proceeds with a constant and rather slow speed. It takes tens of seconds to fully adapt from a bright environment to a very dark one. In contrary, adaptation in the opposite direction from darkness to brightness is very fast and strongly non-linear. At first people are blinded by the light but after a short time they begin to see the objects. During this time, human is adapting to the *adaptation luminance* - the average luminance HVS adapts to considering an arbitrary gaze direction. By measuring the brightness in two separate situations, it is possible to calculate the required time for full adaptation. Therefore, the bigger the difference between current and previous luminance is, the shorter it takes to adapt to the new setting.

The adaptation is *gaze-dependent* which means it takes into consideration the gaze point of the observer. Humans frequently change their gaze direction and try to adapt to different regions. As a result, HVS is in the maladaptation state, in which the adaptation luminance is changing towards a target value but never reaches this value because in the meantime the target is changed.

Models of visual adaptation are used in computer games to make the graphics more realistic and plausible. A noticeable example is the "Uncharted 2" game in which the tone mapping with visual adaptation is implemented. In this game temporal adaptation is applied by assigning fixed spots on the floor, in which the eye should adapt to light or dark. Depending on a place the player has stepped into, view was properly configured. The advantage of this solution is the simplicity of calculations. However, any dynamic light source cannot be used, which can be essential for the realistic simulation [5]. The other technique worth mentioning is the one used in Unreal Engine. Here adaptation is based on the average luminance of the scene. It is also possible to adjust the time needed to adapt to light and dark separately. It is an accurate way of simulation, although it does not take into consideration the actual place where the observer is looking - the gaze point. Example screenshots from Unreal Engine are presented in Fig. 1.

A main goal of this work is to model the visual adaptation process in a correct way in terms of the human perception, so that it could reflect the actual behaviour of HVS. However, the adaptation to darkness lasts even tens of minutes and, from a computer game perspective, it often does not make sense to model this process in the same way as it happens in nature. This adaptation would be too slow for fast modern games.

In this paper, we evaluate whether using the perceptually correct visual adaptation operators is practically justified. We perform an experiment, in which people choose a preferred speed of the adaptation to darkness. To mimic the behavior of HVS, we model the adaptation to brightness based on the perceptual formulas, while the adapta-

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tion to darkness is simulated by the linear luminance transformation. To find the target speed of the adaptation to the dark environment, we vary the adaptation time and ask people to choose the most plausible approach.

Section 2 gives background information how the adaptation process works for different lighting conditions. Section 3 is focused on our game framework and shows how we simulate the visual adaptation mechanisms. Section 4 presents the results of the perceptual experiment evaluating the adaptation to darkness. The paper is concluded in the last Section.

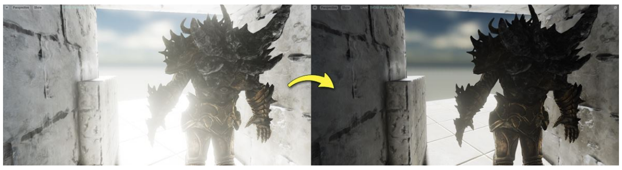

Figure 1: A screenshot generated by the Unreal Engine during (left) and after (right) adaptation to the bright environment [2].

2 Background

In this Section we give basic information on the human visual system and visual adaptation process.

2.1 Rods and cones

Human vision is based on two types of photoreceptors *rods* and *cones* that absorb the light from the environment [18]. The cones allow for colour vision under appropriate lighting conditions, while the rods are responsible for recognizing shapes and monochrome vision in low light conditions.

The colour vision is activated when light interacts with the chromophore inside the visual pigment (opsin) which can be found on top of the cone. There are three kinds of opsin (L, M and S) related to three colours they produce (red, green and blue). The chromophore changes shape and triggers a cone. If at least two kinds of cones are triggered, a signal is sent to the photoreceptor, in which light is converted into an electrical signal, and later transferred to the brain. There are between 6 and 7 million cones with the majority of them being L (64%) or M (32%) types [11]. The "blue" cones (S) represent just 2% of all cones. In comparison to L and M, the S cones are much more sensitive to light and reside outside the fovea.

The rods are activated in low light conditions and are responsible for the scotopic vision, in which people do not see colour but are very sensitive to contrast changes (a thousand times more sensitive than cones) [18]. There are about 120 million of rods and they can be triggered with just individual photons. They adapt to shorter wavelengths than cones, therefore, people see blue objects quite clearly in the dark, while red objects might even be completely invisible. Since all rods are outside the fovea and the highest acuity area, it is sometimes impossible to see an object at which we are directly looking in the dark, e.g. when we want to observe stars in the night. The only way to improve this vision is to look at a star "out of the corner of the eye". Then, it is observed with the part of retina containing mostly rods. The scotopic vision is possible because of the *rhodopsin* pigment on top of the rod. This process is very similar to the one in the cones: when light (at least one photon) strikes the rod, the chromophore changes shape and triggers an electrical signal sent to the brain.

2.2 Visual adaptation

The human eye is able to adapt to luminances which differ greatly, even 14 orders of magnitude - from moonlight ($10^{-6}\frac{cd}{m^2}$) up to sunlight ($10^{8}\frac{cd}{m^2}$) [15]. The *visual adaptation* process takes place when the lighting condition, to which the observer is currently adapted, changes. For example, this happens as a results of someone entering a darker room, turning on the light, or walking outside. The time for the eye to adapt to the new environment depends on whether the cones or the rods are being activated/deactivated.

In the case of increasing the ambient luminance, the photopigment in rods gets bleached [1]. For a few seconds, they are completely blind and the sensitivity of cones begins to increase. The whole adaptation takes up to 5 minutes but the vision might be fully clear in less than one second [8]. During this short period the vision is heavily impaired - the colours are barely visible and all objects seem to be too bright.

During adaptation from bright to dark, a reverse process takes place - at the beginning it is hard to see anything [3]. It is caused by the fact that cones are currently in the low sensitivity state and rods are bleached. Then, cones regain their sensitivity and rods are regenerated. When cones achieve highest sensitivity, rods begin to increase their sensitivity until they are fully adapted.

The adaptation to darkness is a sustained process - depending on the amount of light it could take from 10 minutes to 2 hours, sometimes even more [8]. This process is presented in Fig. 2. From obvious reasons in simulations and computer games this time has to be shortened, so that the observer would not need to wait minutes to see any information.

2.3 Maladaptation

The human eyes mainly adapts to an area covering approximately 2-4 degrees of the viewing angle around the gaze direction [17]. Other areas of the scene, observed not in foveal but in para-foveal and peripheral regions, have significantly less impact on the adaptation level, although, a human frequently changes gaze direction (even a hundred times per second) and tries to adapt to different regions [10]. As the process of the luminance adaptation is

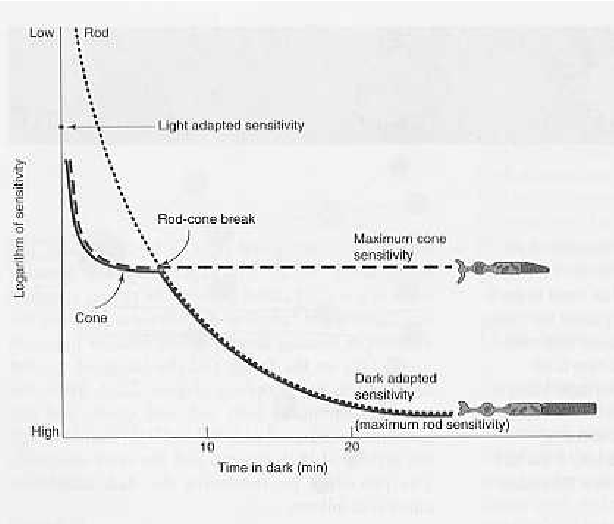

Figure 2: The dark adaptation process (after Gordon et al. [3]).

slower than changes of gaze direction, the HVS is permanently in the *maladaptation* state, in which the adaptation luminance is changing towards a target value but never reaches this value because in the meantime the target is changed.

2.4 Previous work

Visual adaptation has been a topic of several articles. In 1996, the model of visual adaptation was described in [4]. The model discussed in this paper is used for realistic image synthesis which takes into consideration threshold visibility, colour appearance, visual acuity, and sensitivity. It is however only usable in static pictures. Another article, published in 2000, uses much simpler equations [13]. The RGB is created using the adaptation model with very efficient technics. This makes it possible to use in dynamic scenes. The main disadvantage of this method is the fact, that it does not consider the gaze point of the observer. Another article, published in 2004, operates on High Dynamic Range images [8]. It models rods and cones separately, and the local adaptation is computed using Gaussian function. This method is very precise and performs very well in simulations and static images, however in our work we want to produce effects of similar quality with lower performance impact.

3 Test game framework

In this Section we present our prototype game framework. The main goal of this approach is to implement the luminance adaptation models and provide a testbed for the perceptual experiments.

3.1 Implementation

The framework has been implemented in C++ based on the OpenGL library (version 4.0) supported by GLFW for input/output operations, Assimp for loading 3D models, and FreeImage for loading textures. The lighting computations are based on the Phong shading model. We built a scene consisting of 15 objects and approximately 18.000 triangles, which presents the interior of an office. The scene contains very bright object (lamp on the ceiling) and a number of dark objects with a luminance that is lower by almost four orders of magnitude. An example rendering is presented in Fig. 3.

Figure 3: An example screenshot from our test game framework.

3.2 Visual adaptation module

A core module in our framework is the visual adaptation mechanism presented in Fig. 4. We do not use an eye tracker, so the gaze location is assumed to be at the centre of the screen. We compute the weighted average of the pixel luminance from the whole image, wherein the weights are delivered as a texture mask (see Sect. 3.3). The whole process is repeated for each frame taking into consideration the maladaptation mechanism (see Sect. 3.4). The obtained temporary adaptation luminance is used to tone map the image based on the sigmoidal tone curve (see Sect. 3.5). The actual visual adaptation is implemented by varying the global luminance level of the rendered image.

3.3 Spatial extent of visual adaptation

In HVS, the highest impact on the vision has the high-acuity area, the 8-degrees surrounding of the gaze point. Recently Vangorp et al. [17] proposed an adaptation model, in which the local adaptation luminance is based on the pixel values in this area. However, in our framework we apply a simpler approach based on the gaze-dependent contrast sensitivity function [14]. This function roughly follows distribution of the cones in the retina. The *spatial cutoff frequency* is the way of measuring the smallest visible object. It is measured in cycles per milimeter. As the number of cones decreases with the eccentricity, we assume that adaptation luminance is affected mostly at the areas of the highest frequency [9].

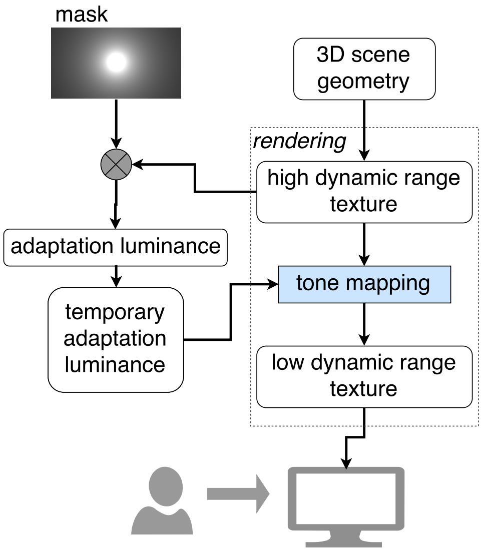

Figure 4: The diagram of the visual adaptation module.

The below equation models the spatial cutoff frequency f_c of the human retina, i.e. the highest frequencies that are still visible for the eccentricity d:

$$f_c = 43.1 * \frac{E_2}{E_2 + d}, \tag{1}$$

where E_2 denotes the eccentricity at which spatial frequency drops to half (we use a value of 43.1 cpd). The graph of this function is presented in Fig. 5. The mask based on this equation is shown in Fig. 6.

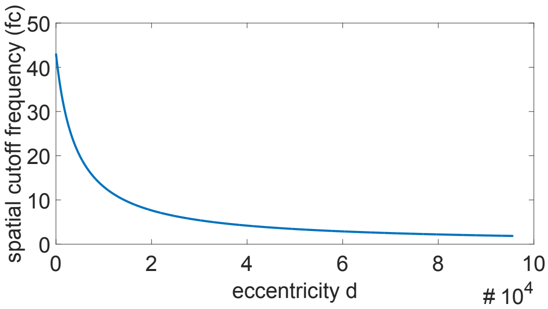

Figure 5: Graph of the f_c function.

3.4 Temporal adaptation

The adaptation luminance changes over time because observers moves their gaze location. As the adaptation time can last longer than the animation frame, the maladaptation state should be considered. For this task we use a shader, which receives the luminance value from the previous and current frames. These values are used to modify the adaptation over time [7]:

$$\widehat{L}_a^{new} = \widehat{L}_a + (\widehat{L}_{HDR} - \widehat{L}_a)(1 - e^{-\frac{T}{\tau}}), \tag{2}$$

Figure 6: The mask used to approximate the adaptation luminance.

where $\widehat{X} = \log_{10}(X)$, L_a^{new} denotes a new adaptation luminance, L_a is the adaptation luminance from the previous frame, L_{HDR} - luminance of the input HDR image, T is the time which elapsed between the display of the current and previous frame, and τ is the adaptation speed. The above exponential function gives the accurate results, however we simplified this approach to a formula:

$$L_a^{new} = \begin{cases} \min(L_a + \frac{T}{\tau_{rod}}, L_{HDR}), & \text{if } L_a < L_{HDR} \\ \max(L_a - \frac{T}{\tau_{cone}}, L_{HDR}), & \text{if } L_a \geq L_{HDR} \end{cases} \tag{3}$$

where τ_{rod} and τ_{cone} indicate rod and cone adaptation time, respectively ($\tau_{rod} = 9.0s$, $\tau_{cone} = 0.1s$). The above equation gives a rough approximation of the exponential formula. Apart from that, it is much simpler and more appropriate for real-time rendering.

As shown in Fig. 7, switching off the lamp starts the slow adaptation to dark (top row). When the lamp is switched on, this process is interrupted and the adaptation to bright begins before the eyes become fully adapted to dark (middle row). After switching off the lamp again, the observer can fully adapt to the darkness (bottom row).

3.5 Tone compression

In our test framework we implemented the sigmoidal tone compression proposed for the gaze-dependent tone mapping in Mantiuk and Markowski [10]. The shader used for this compression converts colour to luminance using the formula: $L = c_r * 0.212656 + c_g * 0.715158 + c_b * 0.072186$, where c_r, c_g, and c_b are the red, green, and blue components, respectively.

The tone compression is based on the Naka-Rushton equation [12]:

$$L_{LDR} = \frac{L_{HDR}}{L_{HDR} + s}, \tag{4}$$

where s denotes the momentary adaptation luminance L_a^{new}.

The output colour values of the rendered image are computed based on the formula [16]:

$$c_{new} = (\frac{c_{HDR}}{L_{HDR}})^s * L_{LDR}. \tag{5}$$

Figure 7: Top row: observer is fully adapted to the bright environment, then the lamp is switched off and slow adaptation to dark begins. Middle row: the lamp is switched on, the eye is blinded by the bright environment but it quickly adapts to the bright environment. Bottom row: the lamp is switched off again, after some time observer adapts to the darkness.

We chose the colour desaturation factor equal to 1.2. Finally, the output image is gamma corrected and presented on the display calibrated to the sRGB colour profile.

Example images rendered for different values of the adaptation luminance are presented in Fig. 8.

Figure 8: *Images rendered for observer adapted to the bright areas (top) and dark area (bottom). The orange cross depicts the gaze location.*

4 Experimental Evaluation

We performed a pilot experiment, in which game players were asked to assess the most suitable speed of the visual adaptation to darkness.

4.1 Stimuli and procedure

During the experiment observers sat in front of the display in a 60 cm distance. They were asked to observe an animation sequence. At the beginning, the grey background with the experiment instruction was displayed. Then, a scene presenting the interior of the room was rendered (see example in Fig. 3). The camera was looking at the bright lamp for 5 seconds, which caused the adaptation to high brightness. Next, the camera smoothly moved from the lamp to the desk, whose luminance was one order of magnitude lower than that of the lamp. The camera remained in this position until the adaptation to dark was finished. The whole procedure was repeated again but for different times of adaptation to dark. Then, the observer had to decide, which adaptation speed was more plausible - the exact question he had been given was 'Which adaptation speed do you like more?'. The answer was provided by moving the slider on the bar which was scaled from -1 ('definitely first') through 0 ('I do not see a difference') to 1 ('definitely second'). The bar was continuous, so that the observer could answer as precisely as possible.

We tested every combination of 2, 8, 16, 25, and 33 seconds, while the pairs were chosen randomly. Each observer repeated the experimental session three times for each pair of the adaptation times.

The experiment was performed in a darkened room. Images were displayed on a 27 LCD display with a native resolution of 2560 x 1440 pixels and a screen width and height of 62.4 cm and 40.1 cm, respectively. The computer was equipped with a Geforce 780 Ti GPU.

Participants

The experiment was performed on a group of 13 volunteer observers (age between 17 and 50 years). They declared normal or corrected to normal vision and correct colour vision. The participants were aware that the visual adaptation is tested, but they were naïve about the purpose of the experiment.

4.2 Results

Fig. 9 presents a bar plot with the results of the experiment, which shows the preference as a function of the speed of adaptation to the dark environment. This preference is a number of votes cast for the adaptation time normalised by a number of times this time has been tested.

The best score was obtained for 2 seconds, however for longer adaptation of 8 seconds the observers' preference is very close to this result (0.7647 and 0.7639 respectively). The obtained results suggest that players prefer shorter adaptation times in comparison with the natural HVS behaviour.

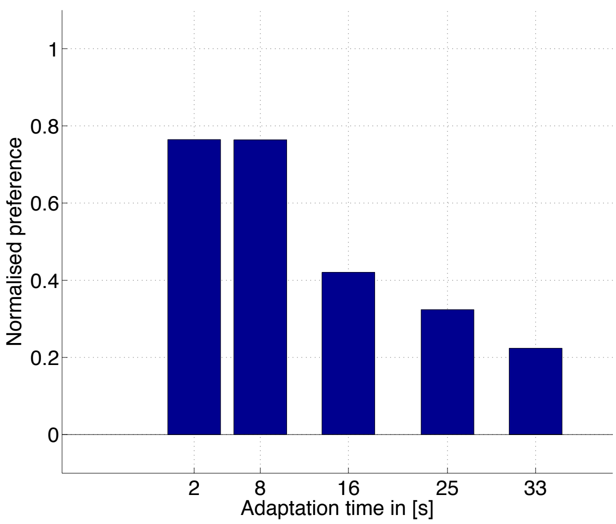

Figure 9: Results of the perceptual experiment studying speed of the adaptation to darkness.

5 Conclusions and future work

In this work, we conducted an evaluation of the preferred speed of the visual adaptation to darkness. We implemented a test game framework supporting the adaptation to both dark and bright environments. In this framework the output rendering is tone mapped using the global compression curve, whose shape is modified based on the adaptation luminance value. This value is computed using the weighted average luminance of the scene. The adaptation luminance is changed over time to simulate the maladaptation conditions.

We performed an objective experiment, in which a number of adaptation times to darkness were compared. The results revealed that the most favourable is adaptation lasting 2 and 8 seconds, which is in contrast to the physical model of the human visual adaptation suggesting much longer timings.

Our study approaches the problem of the adaptation speed from a perspective of computer games. Even though we proved that the users prefer quicker adaptation, it might not be true for every game time. Our solution is well-suited for the games based mainly on exploration and the analysis of the environment. Games which require higher level of realism, like simulators, would look better with longer adaptation. Long adaptation could be also used as an obstacle of some sort, e.g. in the First Person Shooter games - the adaptation time could make it harder to spot enemies and it would be necessary to adapt new tactics.

In future work we plan to conduct perceptual experiments that assess the game player's preferences towards a model of the adaptation to brightness. We would like to check whether a complex non-linear mechanism is really needed during the gameplay. Also, we plan to implement gaze-dependent adaptation controlled by an eye tracker and evaluate if this local adaptation is more preferable than the simplified approach based on adaptation to the screen centre. Another implementation worth investigating are the human saliency models [6] that do not require an eye tracker and could point out direction of the observer attention.

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