Perception of Light in Virtual Reality

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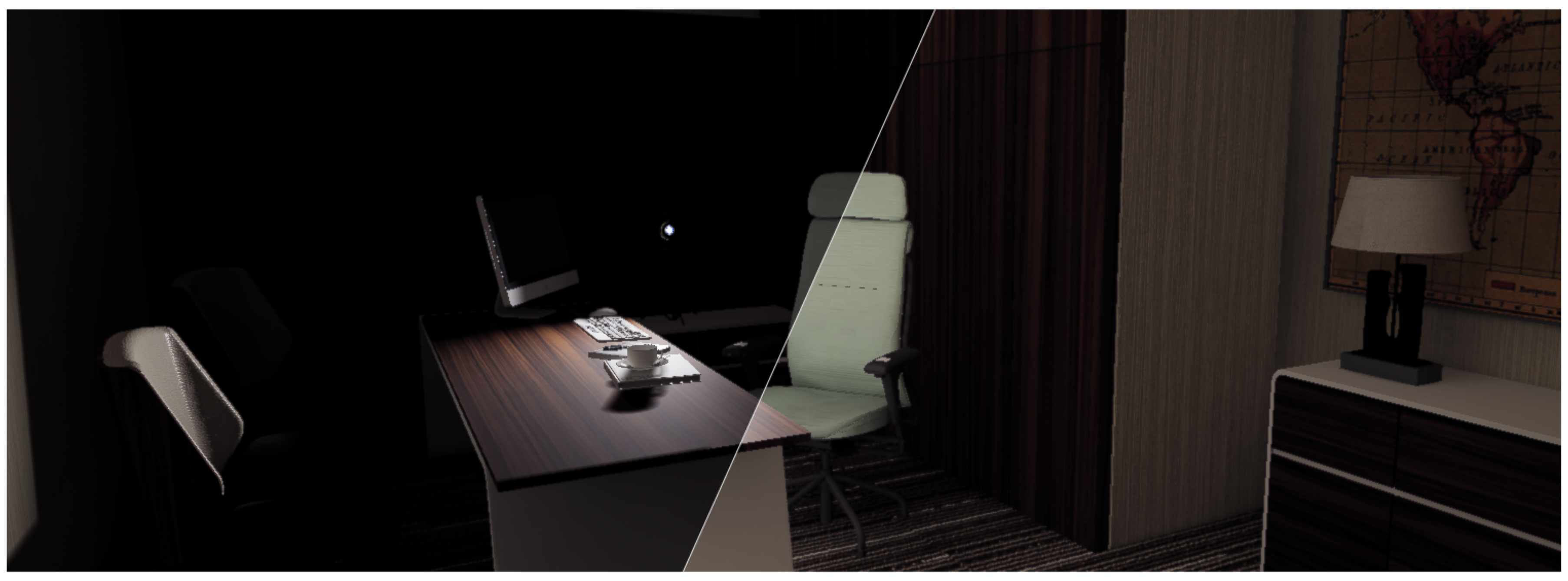
Overview

Human vision is highly dependent on the way light enters the eye: we see a pulsing corona when looking at bright light sources, or our color perception changes during night-time. These phenomena do not appear naturally when looking at a screen – the displayable luminance range only covers a small part of the range perceivable by a human. To achieve a realistic representation of bright light sources or light in general we need to simulate them. Perceptual algorithms need to respond to different lighting conditions in a similar way the actual human eye responds to them. Therefore, we developed a new post-processing workflow for perceptually more accurate light simulation in virtual reality (VR) using eye tracking, which can be used for vision impairment studies or evaluating lighting conditions for architectural room planning.
The image below shows a low-light scene rendered with the *Unreal Engine* default settings.

Temporal Eye Adaptation

Temporal eye adaptation occurs when the luminance of the focused region changes – depending on external influences like a light switching on or off, or simply our viewing direction. This adaptation does not happen instantly but converges over time to the optimal adjustment for a given brightness, due to the varying destruction of proteins in the eye when hit by light and their constant reconstruction speed.
We simulate temporal adaptation by applying an increase or decrease of the average luminance of the frame following a medically determined, exponential function over time. We calculate the frame luminance weighted by the user's viewing direction, which gives the currently focused area more impact and the periphery becomes less important.
The image below compares initial scene adaptation to a converged adaptation after 5 seconds.



Perceptual Glare

The humanly perceived glare is generated by particles in the eye scattering light rays. Humans do not only see a single sharp, bright area but a flickering corona around a light source. This is medically based on the fact that there are impurities in the structure of the human eye that diffract the incoming light. Using the diffraction of light on a slit or aperture, such as the pupil, and including the impurities of the eye, the resulting pattern can be simulated by calculating the point spread function (PSF) of an eye, which approximates the spreading of light on the retina.
We measure the user's pupil size and calculate the aperture size in real time. Additionally, the current viewing direction is used to adapt the intensity of the displayed glare when not focusing on the light source directly.
The image below compares a common bloom to our perceptual glare.

Visual Acuity Reduction

Especially in dark scenes, the human eye suffers from loss of visual acuity. The photoreceptors in the eye that are mainly active during mesopic and scotopic vision, the rods, are not present in the fovea, which is the point of sharpest vision in the eye. Therefore, in low-light conditions, we only receive signals from regions in the eye that are not optimally in focus.
This effect influences only the pixels that are below a specific brightness – for humans 10 cd/m^2. However, computer screens are not able to represent such low luminances. These pixels have to be adapted by blurring them with a Gaussian filter depending on its luminance. We propose a new function fit to approximate the loss of visual acuity in the dark.
The image below shows bright and dark regions to illustrate visual acuity reduction – in the bright region the map is clearly visible, while it is blurred in the dark.

Scotopic Color Vision

Human color perception changes under low-light conditions. This is because rods are only able to see "one color", and are not able to distinguish between thee different wavelengths of light like cones. Therefore, we perceive a blueish color shift at night time or dimly illuminated scenes. This effect cannot appear naturally when looking at a monitor since the minimum displayable luminances still trigger the cones in the eye. However, to realistically simulate a scene that is not well lit, the shift in color vision in mesopic and scotopic conditions has to be taken into account.
We use the sensitivity function of scotopic vision to apply a color shift towards lavender purple if the rod-vision is activated, because of the perceptual change towards light blue to purle at night.
The image below compares an image without color adaptations to our scotopic color vision approach.

Results

Our approach was implemented as a real-time VR post-processing toolbox that can be added to any common renderer. We conducted a user study, where we asked five participants to compare their own vision to our VR application and rate the similarity of each effect. Our results show that visual perception is different for each participant, yet overall our simulation was able to give the impression of a realistic scene. However, further improvements are necessary in glare appearance to allow for full realism.
With this user study, which was the first of its kind to our knowledge, we were able to show the importance of medically based, perceptual effects to increase the quality of visual perception in VR, which leads to more realness of the simulation and finally also better immersion.
The image below shows all our simulated effects.