Perceptually Based Afterimage Synthesis

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Abstract

Afterimages comprise a common, recurring perceptual phenomenon experienced in a daily-basis. Afterimages are best realized when staring at some high intensity light source (i.e., a light bulb) and then shifting the ocular focus to other less luminous portions of the scene: a temporary "ghost" image of that strong intensity remains imprinted on the retina. During the time the afterimage stays active, several exquisite color gradations appear and fade. Although research on the topic has been moderately active in ophthalmology and vision domains, no definitive model has been devised. Furthermore, no afterimage simulation seems to have yet been investigated in computer graphics. In this paper we attempt to introduce the topic to the field and therefore widen the research spectrum of computer graphics. The proposed technique is based on psychophysical and physiological evidence, addressing the color transitions and the duration of the effect. The method is also fast and suitable for real-time applications. Our stance towards afterimages is more than just curiosity on this peculiar effect: we believe that its understanding and proper simulation can assist on relevant tasks such as urban and road engineering for safer pedestrian and vehicle mobility at adverse lighting conditions.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—I.3.7 [Computer Graphics]: Three-Dimentional Graphics and Realism—

1. Introduction

Photorealistic rendering is the ultimate goal of computer graphics and is often associated only with the physically-accurate transport of light within a scene. Another less acknowledged facet of photorealistic rendering is the simulation of perceptual effects of the Human Visual System (HVS), that is, how light is *perceived* by an individual as opposed to how light *arrives* at the retina.

A challenge behind perceptual effects is the inability of performing accurate measurements. The mechanism of how the human eye is wired together and its signals interpreted by the brain is complex and still indefinite, narrowing the study to subjective experiments. The investigation on perceptual effects remained largely confined to committed vision researchers. Today perceptual effects are part of graphics engines and production pipelines, as can be seen in recent films, games and simulators. The graphics industry has noticed that the reproduction of such effects does not need to be accurate to feel plausible due to its subjective nature.

Afterimages consist of instances of perceptual effects experienced in a daily-basis. Staring at a bright portion of a scene for some period of time and then shifting the attention to another less bright portion yields a still image imprinted in the retina. The patterns present on this burnt image vary in tonality and duration, with peculiar colors far from the tone that originated them transitioning in succession. Afterimages can be categorized as *positive*, with bright and dim parts of the afterimage corresponding to those of the originally observed scene, or *negative*, where the bright and dim parts become reversed. This paper focuses on the less understood *positive* ones, and any subsequent reference to the term afterimage in this paper refers to a positive afterimage. The phenomenon investigated in this paper should not be confused with *light trail* shaders which only simulate the fading of *comet-like* trails on motion blur effects without caring how the color transitions happen in the afterimage [HSE93].

We believe this to be a pioneer attempt in computer graphics to simulate afterimages. The proposed method deals with the *color transitions* and the *duration* of the effect, all based on previous psychophysical experiments and physiological evidence. The technique is *fast* and can be incorporated into existing real-time graphics pipeline. We feel that simulating afterimages transcends pure aesthetics and can be a valuable asset on urban and road engineering efforts for safer pedestrian and vehicle mobility in adverse lighting conditions.

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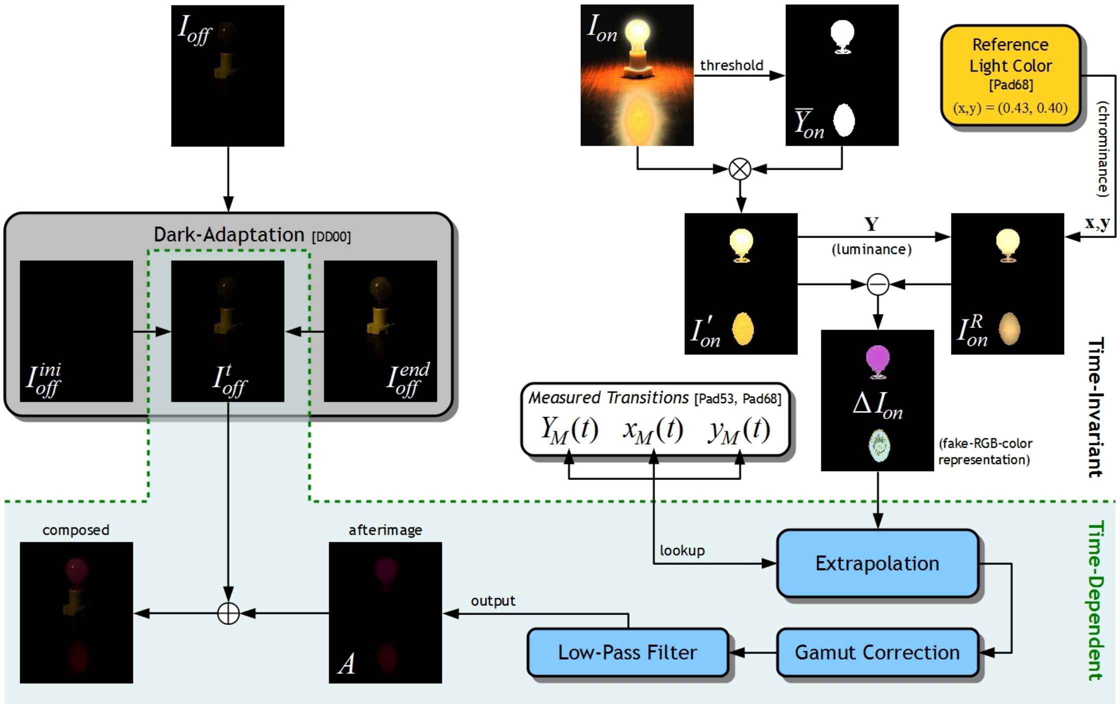

Figure 1: *Overview of the proposed afterimage simulation algorithm.*

2. Related Work

Renowned natural philosopher Isaac Newton was so curious about afterimages to the point of becoming a victim of the phenomenon [Wes80]. The scientist stared directly at the sun for prolonged periods of time, then turning his attention into dark corners of his chamber in order to observe the chromatic transitions. This eventually caused temporary damage to his retinae that lasted for many months (solar scotoma). Newton is said to have "left the sun alone" after the incident.

Recent studies on afterimages have proceeded more carefully. Titchener [Tit01] conjectured that afterimages were caused by excitatory-inhibitory chains in opponent-color systems, inspired by the ideas of Ewald Hering (the actual presence of opponent systems in the HVS was only validated decades later by Hurvich and Jameson [HJ55]). Shuey [Shu24] compiled a survey of several experiments on afterimages. Following that, *color naming* methods were used to measure chromatic transitions at largely *discrete* steps [Wev25]. For example, a positive afterimage caused by exposition to white light yields transitions of blue, yellow, green, carmine red and bluegreen, but little was recorded regarding the *continuous* transitions between these colors.

More sophisticated studies were performed by Padgham, using color matching techniques to study the continuous transitions between colors in afterimages [Pad68], as well as luminosity transitions and the overall duration of the phenomenon based on the total exposition time [Pad53]. Padgham only registered his own subjective experience, validated consistently through multiple occasions, without experimenting with other test volunteers.

It must be reemphasized that the background reviewed here comprises investigations of subjective matter. The precise neurophysiological mechanism behind afterimages remains largely hazy. Nonetheless the research initiatives listed above have motivated us to apply some of these theories and experimentally measured data to a computer model to synthesize afterimages. Therefore, the technique to be described should by no means be taken as a definitive solution for afterimage simulation, but rather as a fast and accessible framework that introduces and briefly investigates the phenomenon of afterimages in the computer graphics domain.

3. Method

The proposed afterimage simulation technique builds upon the observations of Padgham [Pad53, Pad68]. For completeness and additional realism, we have also incorporated a dark adaptation mechanism to the method, as described in [DD00]. This way, while the afterimage is transitioning, the background scene slowly adapts to low lighting conditions on which the afterimage is superimposed. An overview of our entire afterimage reproduction algorithm is shown in Figure 1, depicting the majority of the symbols and definitions that will be introduced in this section.

The process requires two images, I_{on} and I_{off}, depicting the observed scene *with* and *without* the light intensity that originates the afterimage, respectively. Figure 1 (top) depicts a possible configuration for these input images: one has a light bulb turned on, while the other has it switched off.

The goal is then to mimic the color and intensity transitions of the afterimage produced when I_{on} turns into I_{off}. To that end, we based our simulation on the color/luminosity transitions registered by Padgham [Pad53, Pad68]. The first difficulty comes from the fact that Padgham based his experiments on a single isoluminant light pattern, which is not guaranteed to match the scene being experienced in I_{on}. The solution we have devised uses Padgham's fixed light color and intensity as a starting *reference* in order to incrementally *extrapolate* the synthesized afterimage, based on the differences between I_{on} and this reference color.

First, we threshold the luminance of I_{on} to obtain a binary mask $\overline{Y}_{on}$ on where the afterimage will have effect. This mask is then overlaid on top of I_{on} and both multiplied together, thus restricting the region of interest in I_{on} to I'_{on}. Following that, the luminance component of I'_{on} is combined with the chromaticity components of the reference light color used by Padgham, yielding an intermediate image I^R_{on}. This last step is performed in the **Yxy** color space (which is converted from the CIE **XYZ** color space) since it is capable of decoupling luminance and chrominance information. Therefore, the luminance component **Y** of each pixel in I^R_{on} is the same as in I'_{on}, but the chromatic components **x** and **y** remain constant throughout all pixels of I^R_{on}, namely (**x**,**y**) $= (0.43, 0.40)$.

Following that, a per-pixel normalized difference between I'_{on} and I^R_{on} is computed in the CIE **L*a*b*** color space, as defined below (the L*a*b* asterisks are omitted for clarity):

$$\Delta a(i,j) = \frac{\delta a(i,j)}{\delta E(i,j)} \quad , \quad \Delta b(i,j) = \frac{\delta b(i,j)}{\delta E(i,j)} \tag{1}$$

such as,

$$\begin{aligned} \delta a(i,j) &= a'_{on}(i,j) - a^R_{on}(i,j) \\ \delta b(i,j) &= b'_{on}(i,j) - b^R_{on}(i,j) \\ \delta E(i,j) &= \sqrt{\delta a(i,j)^2 + \delta b(i,j)^2} \end{aligned}$$

where $a'_{on}(i,j)$ and $a^R_{on}(i,j)$ correspond to the **a*** component of the **L*a*b*** triplet of the pixel located at (i,j) in the I'_{on} and I^R_{on} images, respectively (notation is analogous for **b***). The motivation behind this particular color space comes from the fact that afterimages are associated with the opponent-color systems in the HVS: the **L*a*b*** color system is not only an opponent-color space, but also keeps color distances in a nearly HVS-compatible and perceptually-uniform fashion.

This difference image ΔI_{on} is an attempt to make a correspondence between the color of each pixel in the input image I'_{on} with those in the reference light color in I^R_{on}. This difference image is important for the extrapolation stage that follows, which is where the actual afterimage is synthesized.

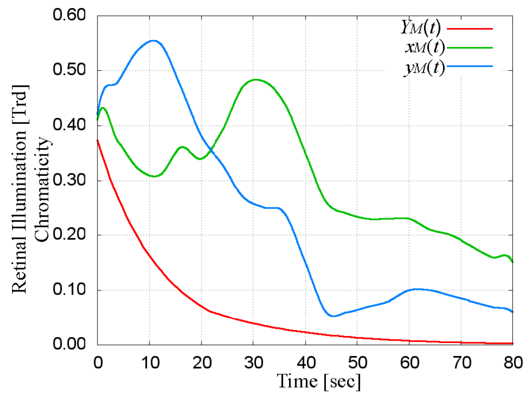

Figure 2: *Chrominance and luminance transitions of afterimages in the* **Yxy** *color space according to the elapsed time as experienced and recorded by Padgham [Pad53, Pad68].*

The rationale behind our extrapolation strategy is to use the *flat* afterimage patterns of the reference light observed by Padgham [Pad53, Pad68] as a base ground and incrementally enhance it by adding image-specific details on top of it (these details are encoded in ΔI_{on}). An afterimage frame A at some instant t can be obtained in the **L*a*b*** space as follows:

$$\begin{aligned} L_A(i,j)_t &= L_M(t) \cdot Z(i,j) & (2) \\ a_A(i,j)_t &= a_M(t) \cdot Z(i,j) + \tau_M(t) \cdot \Delta a(i,j) & (3) \\ b_A(i,j)_t &= b_M(t) \cdot Z(i,j) + \tau_M(t) \cdot \Delta b(i,j) & (4) \end{aligned}$$

with,

$$Z(i,j) = \left(\frac{L_{on}(i,j)}{L^{max}_{on}} \right)^{\gamma}$$

where $a_M(t)$, $a_M(t)$ and $L_M(t)$ are retrieved from the original measured experiments of Padgham, as depicted in Figure 2 (conversions from **Yxy** to **L*a*b*** are implicit). $Z(i,j)$ determines the luminance distribution of the afterimage, while keeping the chroma of the reference; the parameter γ is useful for adjusting the luminance of the reference afterimage. The term $\tau_M(t)$ is simply the image of the function $L_M(t)$ normalized to the range $(0,1]$, that is, $\tau_M(t) = L_M(t)/L_M(0)$.

When the **L*a*b*** triplet obtained from Equations 2–4 is converted to **RGB** for presentation purposes, some pixels are prone to lie outside of the supported gamut of the display device. This happens because the **Yxy** measurements of Padgham are HVS-related and therefore broader than display devices. Consequently, the resulting **RGB** triplet may contain negative values. We fix this issue in two simple steps: first we clamp any negative **RGB** components to zero; second, since clamping affects the luminance of the pixel, we force the pixel luminance to that before the pixel was corrected (this last step is accomplished in the **L*a*b*** color space).

At this point, the afterimage is almost ready to be displayed. The missing task is to apply a low-pass filter to the

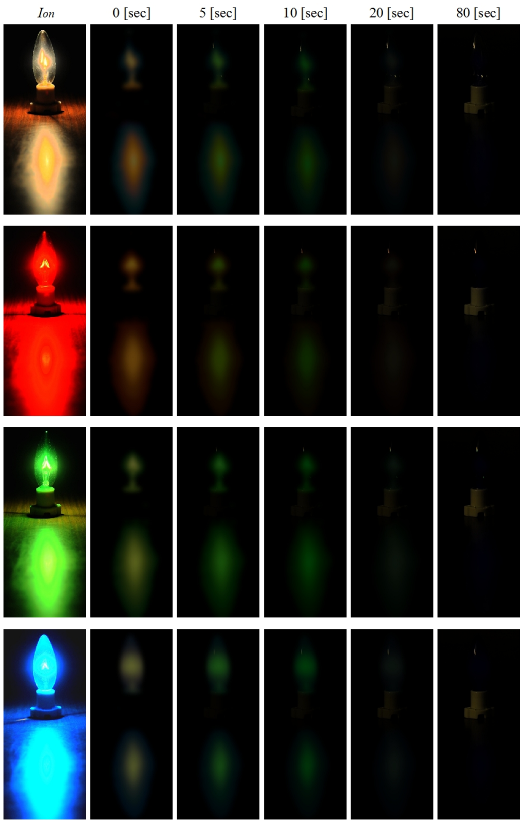

Figure 3: *Afterimage transitions of various light bulbs simulated according to the proposed technique.*

afterimage frame using a fixed-size Gaussian profile. This is necessary because afterimages do not retain much high-frequency details and tend to be perceived blurry.

Finally, and for completeness only, we have decided to blend (additively) the afterimage A on top of a gradually dark-adapting image computed from I_{off}. The process of dark-adaptation that we have employed is described in [DD00]. In short, dark-adaptation is performed by simple interpolation of two images (derived directly from I_{off}) with an exponentially decaying blending weight that varies according to the elapsed time parameter t.

4. Results and Discussion

Results of the proposed afterimage technique are shown in Figure 3 at several discrete snapshots of the simulation. The filament wire of each light bulb is the same, which means that the observed light color is a consequence of the surrounding glass paint coating only. In all simulations the luminance threshold for the afterimage mask was (empirically) set to the top 5.0% largest luminance of I_{on}, and $\gamma = 0.7$.

Interestingly, even though our simulation is restricted to Padgham's measurements [Pad53, Pad68] where only a single light color is considered – akin to the yellowish one at the top of Figure 3 – we found that the simulated chromatic transitions of the afterimages resulting from the other colored lights are in *conformance* to the color measurements recorded by Weve [Wev25]. This observation not only provides and important link between the experiments of Weve and Padgham, but also endorses the effectiveness and robustness of the proposed afterimage color extrapolation scheme.

5. Conclusion and Future Work

In this paper, we introduced a technique to render positive afterimages. The proposed method is perceptually-based, built upon previous psychophysical experiments and physiological evidence. To our knowledge, this seems to be the first attempt to simulate afterimages in the computer graphics literature. We consider our technique fast enough to suit interactive applications. Our algorithm is also orthogonal to other perceptually-based techniques, as demonstrated with the dark-adaptation mechanism, meaning that that it can co-exist non-intrusively with other perceptual effects in the application pipeline. We imagine afterimage effects applicable not only to entertainment media, but also to planning tasks in urban and road engineering for safer pedestrian and vehicle mobility in adverse lighting conditions.

As a future work we would like to validate the results of our simulation through experiments with test subjects. We would also like to investigate the impact of the light exposure time on the afterimage duration.

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