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NONLINEAR MAPPING OF THE LUMINANCE IN DUAL-LAYER HDR DISPLAYS

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Quantization in digital displays

Digital displays are able to reproduce a *discrete* set of luminance levels

- Typically, 256 levels per color channel (8-bit input)
- 10-bit prototypes are starting to appear

The human visual system (HVS) has a *nonlinear* response to luminance

In order to reduce the visibility of the quantization noise, a non-uniform distribution of the levels is used: *gamma correction*

Luminance mapping in digital radiography

An x-ray detector / CT scanner measures the density of the patient's tissues

The density must be converted to luminance values for display

- Film-based radiography: characteristic curve of the film
- Digital radiography: look-up table

The mapping should guarantee a uniform visibility of the details in the entire luminance range

Example: Linear mapping

The DICOM Grayscale Standard Display Function

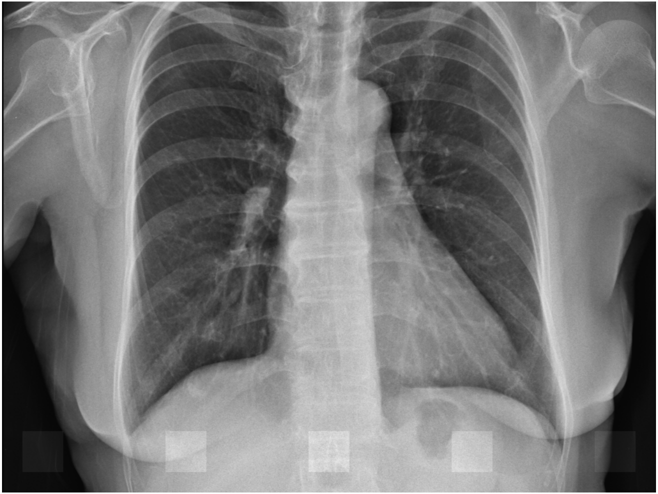
The current technical recommendation defines a mapping curve: *DICOM Grayscale Standard Display Function*

Objectives:

- Equal differences in density produce the same difference in *perceptual* brightness, regardless the background
- The mapping adapts to the luminance range of the display device

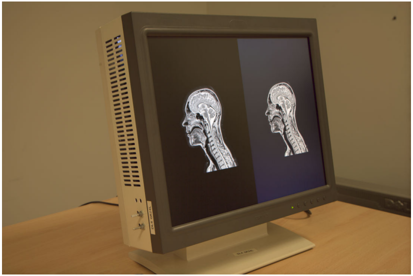
Based on an analytical model of the human contrast sensitivity, introduced in the 1990s by Peter G. J. Barten

Example: DICOM mapping



High dynamic range displays

High dynamic range (HDR) displays are beginning to appear



Example: *dual-layer* liquid crystal displays, under development at FIMI-Philips

- Two liquid crystal panel stacked one on top of the other
- Enhanced backlight unit

DICOM mapping on HDR medical displays

The DICOM curve produces poor results on HDR displays

- Dark images
- Poor visibility of the details in dark areas

Explanation:

- Barten's model *overestimates* the eye sensitivity at low luminance levels
- Loss of contrast due to the the ambient light

In this work, we attempt to address these issues

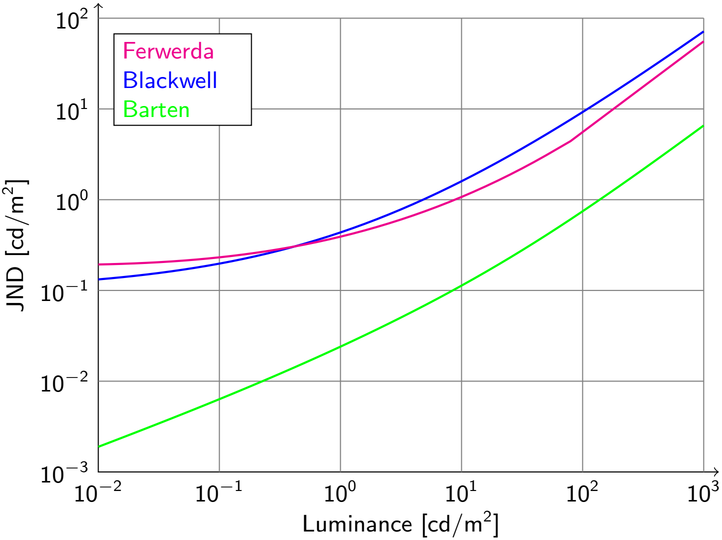
Proposed method – Background

The eye sensitivity is quantified using the concept of *just noticeable difference* (JND)

- Represents the minimum luminance variation an average observer can detect
- Estimated in *detection threshold* experiments
- Increases with the background luminance, following a *threshold versus intensity* (TVI) function

The measured TVI function heavily depends on the experimental setup
$\Rightarrow$ Different expressions have been proposed in the literature

Comparison of TVI functions



Objectives

We wish to generate a *perceptually uniform* scale of n luminance levels L_j such that

$$L_{j+1} - L_j = \frac{k}{2} \left[\mathrm{TVI}(L_j) + \mathrm{TVI}(L_{j+1}) \right] \qquad \forall j$$

Constraints

- $L_1 = L_{\min}$ (display black level)
- $L_n = L_{\max}$ (display white level)

Step 1: Luminance to perceptual brightness

As a starting guess, generate a scale of n logarithmically-spaced luminance levels L_j between $L_{\min}$ and $L_{\max}$

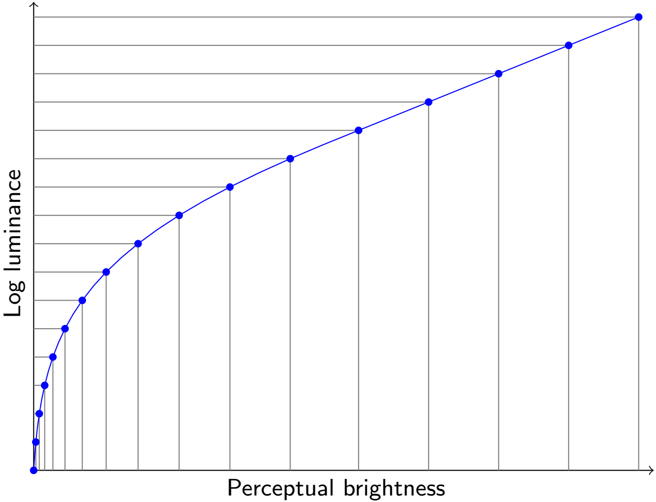
Compute the perceptual distance between each pair of adjacent levels

$$\Delta P(L_j, L_{j+1}) = \frac{2(L_{j+1} - L_j)}{\mathrm{TVI}(L_j) + \mathrm{TVI}(L_{j+1})}$$

Compute the perceptual brightness P_j corresponding to each L_j by accumulating the ΔPs

$$P_1 = 0 \qquad P_{j+1} = P_j + \Delta P(L_j, L_{j+1})$$

Step 1: Luminance to perceptual brightness



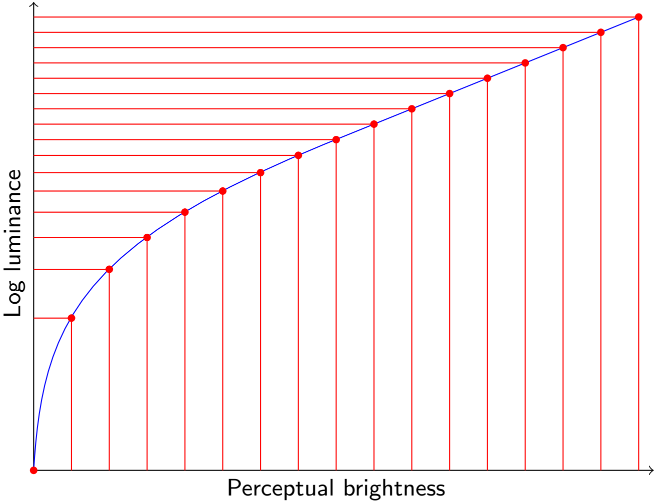
Step 2: Perceptual brightness to luminance

The perceptual brightness values P_j computed in the previous step are unevenly spaced in general

In order to generate a perceptually uniform scale

- Generate n uniformly spaced perceptual brightness values $\hat{P}_j$
- Compute the corresponding luminance levels $\hat{L}_j$ by interpolating the curve

Step 2: Perceptual brightness to luminance



Step 3: Iterative refinement

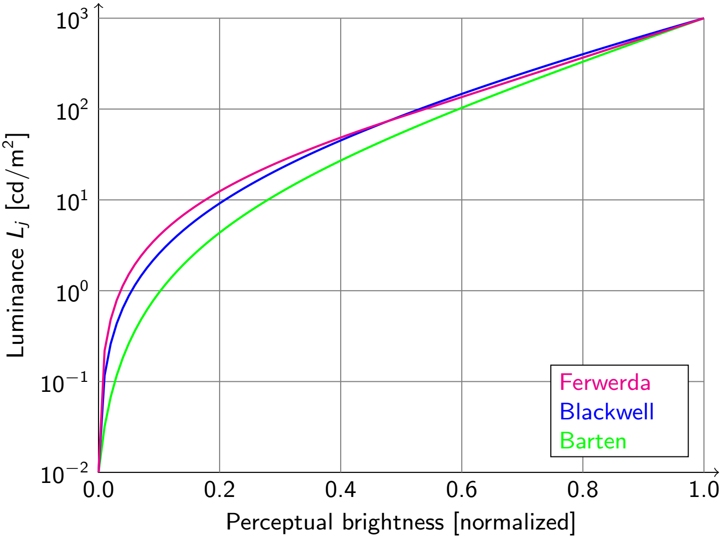
Some error is still present due to the interpolation

In order to remove the interpolation error, iterate the algorithm

- Compute the perceptual distance $\Delta P(L_j, L_{j+1})$ between the levels
- Compute the perceptual brightness by accumulating the distances
- Divide the horizontal axis into equal intervals
- Compute the luminances by interpolating the curve

Usually, 1 – 2 iterations are enough for convergence

Results


10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Luminance L_j [cd/m^2]
0.0
0.2
0.4
0.6
0.8
1.0
Perceptual brightness [normalized]
Ferwerda
Blackwell
Barten

Results

The plots of the mapping curves show that

- Barten's model produces dark images
- The difference between the models becomes considerable when the luminance range is large

Observer studies showed that Ferwerda's model produces the most uniform detail visibility in the entire luminance range

Ambient light compensation

HDR displays can reproduce luminance levels below the ambient light

If no correction is performed, the ambient light can mask the details in the dark areas.

Proposed solution

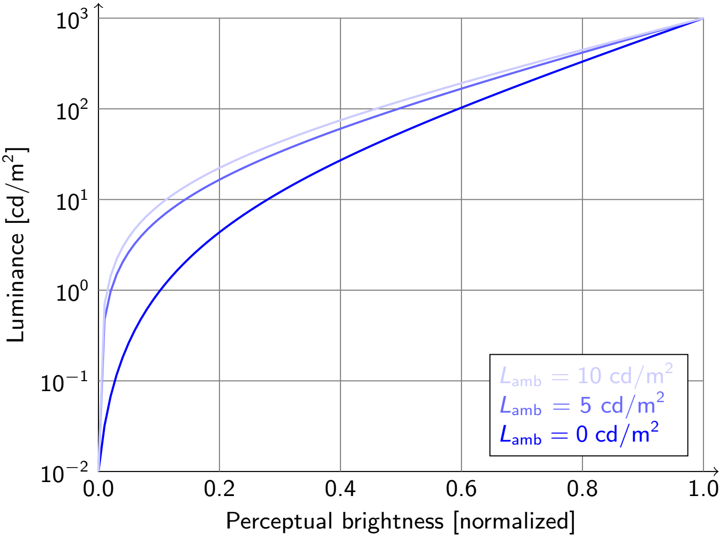
The light which reaches the observer's eye is equal to the sum of

- Luminance emitted by the display: L_j
- Ambient luminance reflected by the screen surface: L_{amb}

We generate a corrected luminance scale by replacing $\text{TVI}(L)$ with $\text{TVI}(L + L_{\text{amb}})$ in the algorithm

The luminance levels of the corrected scale have the same perceptual distance after L_{amb} is added

Results


10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Luminance [cd/m^2]
0.0
0.2
0.4
0.6
0.8
1.0
Perceptual brightness [normalized]
$L_{amb} = 10$ cd/m^2
$L_{amb} = 5$ cd/m^2
$L_{amb} = 0$ cd/m^2

Results

The ambient light compensation increases amplifies the details in the dark areas and improves their visibility

The available luminance range is fixed
$\Rightarrow$ The compensation *inevitably* attenuates the details in the bright areas

A suitable trade-off must be found

Conclusions

In this study we

1. Investigated the luminance mapping techniques used in the display of radiographic images
2. Identified the issues involved when using HDR displays and the limitations of the current technical recommendation
3. Compared different models for the luminance response of the HVS
4. Proposed a fast and accurate algorithm for the computation of perceptually uniform luminance scales
5. Proposed a technique for the compensation of ambient light

Experimental assessment

We are currently performing observer studies, in cooperation with the Center for Devices and Radiological Health of the US Food and Drug Administration

Objectives

- Quantify the clinical benefit of displays with increased luminance range and bit depth
- Compare different mapping techniques

Methodologies

- Task-based objective quality assessment, measuring the detectability of specific targets in the displayed image
- Both natural images and synthetic test patterns
- Both human and computational observers

Open problems

The mapping curves used so far are space-invariant

Limitations of the model

- The eye sensitivity depends not only on the point-wise luminance, but also on the surroundings: *local adaptation*
- Some light from the bright areas is scattered inside the eye: *veiling glare*

These effects further reduce the visibility of details in the dark areas, and are especially critical on HDR display devices

Future work

We are currently investigating techniques which compensate the effect of local adaptation and veiling glare

Main issues:

- Lack of accurate models
- Variability between different observers
- Dependence on the observer position and the environment

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Further information on dual layer LCD displays available at
http://www.fimi.philips.com/displays-innovation/white-papers