Entanglement of Color Management Components in a Whole-Slide Imaging System

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Abstract
An electronic tool, *pixel meter*, was designed to inspect the color management in a whole-slide imaging (WSI) system. Pixel meter is a reconfigurable circuit that retrieves the digital pixel values transmitted from the computer to the display device on the display visual interface that are not accessible by means of software. Five color management components were examined, including the WSI review software, color calibration kit, color manager, graphics card driver, and display color space. The pixel meter was used to determine how the scanner/display color profiles were used by the WSI review software, the limitation and variability in five color calibration kits, the incompatibility between color profiles generated by three different manufacturers, and the confounding effects introduced by the graphics card driver. Unexpected behavior was also detected when components from different manufacturers were mixed-and-matched in the color management system.

Purpose
The goal of this study is to demonstrate the impact of various components of color management in a WSI system and the variability of color calibration kits.

Methods

Background. The overview of this study is illustrated in Figure 1 based on the imaging chain of the WSI display subsystem, which accepts an image file and generates optical signals [1]. The imaging chain consists of the *WSI review software*, *computer environment*, and *display device*. The WSI review software relies on the hardware and software services provided by the computer environment. The display device reproduces the WSI image to the human reader.

The basic idea of color management is to compensate for the uncalibrated scanner/display errors by modifying the red, green, and blue (RGB) pixel values received from the WSI Review Software ($RGB_{original}$ in Figure 1) before they are sent to the display ($RGB_{display}$). The *color profile* contains the color transformation for a specific scanner/display device. The color profile is generated by a *color calibration kit (CCK)*, which measures the display with a color sensor and then calculates the optimal color transformation and saves it in a color profile. The *color manager* controls which color profile to use and how. The *graphics card driver* executes the color transformation and frequently offers extra features, such as gamma curve adjustment and color enhancement.

Tracking the color management is challenging because the color transformation process is hidden from the end user. From the WSI review software to the display device, the RGB values can be altered in three stages. First, the WSI review software may or may not convert $RGB_{original}$ into $RGB_{capture}$ based on the color transformation described in the scanner and/or display color profiles. Second, the designated color manager converts $RGB_{capture}$ into $RGB_{managed}$ based on the default color profile, which is not always obvious to the end user. Third, the graphics card driver may convert $RGB_{managed}$ into $RGB_{display}$ based on the user's preferences without the color manager's awareness. Although $RGB_{capture}$ can be inspected with software tools such as the Windows Snipping Tool, $RGB_{managed}$ and $RGB_{display}$ cannot be probed unless a proper hardware tool is commissioned.

Pixel Meter. A field-programmable gate array (FPGA) board (Altera DE2 Board and DVI-HSMC Card, Terasic, Hsinchu, Taiwan) was programmed to intercept the 8-bit RGB values of the center pixel on the Display Visual Interface (DVI), which connected a color display (HP DreamColor Z24X) with the computer (Windows 7 Professional 64-bit). The RGB value was displayed on the FPGA board in real time at a 60 Hz refresh rate for visual readout. The RGB value was also transmitted to another computer via the RS232 serial communication port at 1 Hz for batch mode testing [2].

With the pixel meter, it took less than 3 minutes to digitally measure the RGB values of 140 color patches. In contrast, it took a spectroradiometer (e.g., CS-2000A, Konica Minolta Sensing Americas, Inc., New Jersey, USA) more than 30 minutes to optically measure the spectra from the display, which are hardly repeatable due to the temporal variability in both the display and the spectroradiometer.

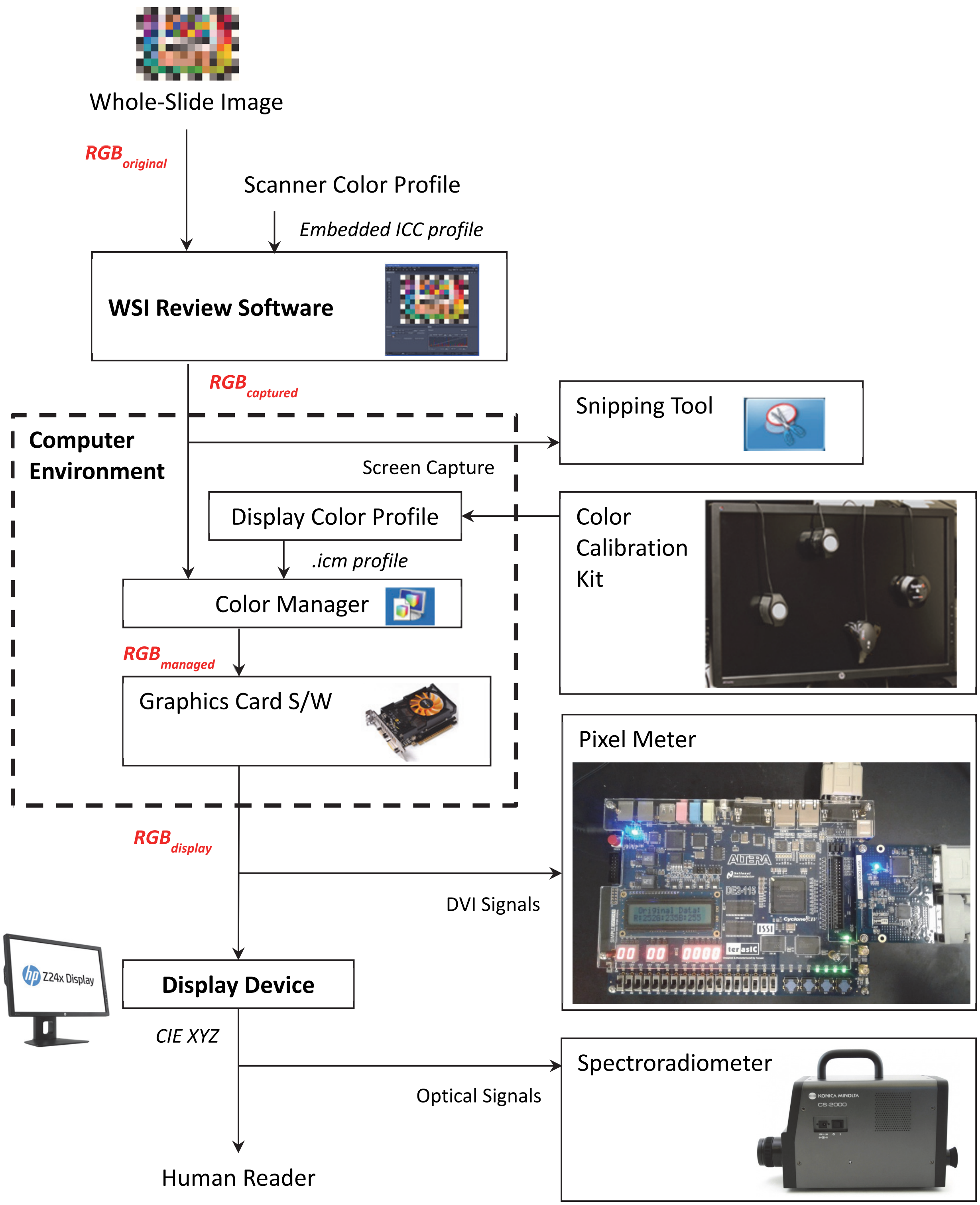

Figure 1: Dataflow of color management in a WSI display subsystem -- from image to display. See Method/Background for detail.

Table 1: Control variables and test cases

<table>
<tr><td>WSI Review Software</td><td colspan="4">Zeiss ZEN2 ver. 2</td><td colspan="4">Aperio ImageScope 12.2.2.5015</td></tr>
<tr><td>Color Calibration Kit</td><td>Windows
Display Color Calibration</td><td colspan="2">X-Rite
i1 Display Pro</td><td colspan="2">X-Rite
ColorMunki</td><td colspan="2">DataColor
Spyder 4</td><td>DataColor
Spyder5</td></tr>
<tr><td>Color Manager</td><td colspan="2">Windows
Color Management</td><td colspan="4">ColorMunki</td><td colspan="2">Spyder4
ProfileChooser</td></tr>
<tr><td>Graphics Card Driver
(nVidia driver 347.52)</td><td colspan="4">Gamma</td><td colspan="4">Digital Vibrance</td></tr>
<tr><td>Display Color Space
(HP ColorDream Z24X)</td><td colspan="2">sRGB</td><td colspan="4">Adobe RGB</td><td colspan="2">Native</td></tr>
</table>

WSI review software. Zeiss ZEN2 and Aperio ImageScope were tested. A digital 140-patch color target in the proprietary WSI file format was used as the input image.

Color Calibration Kit. A professional grade monitor (HP DreamColor Z24X) was used for the CCKs to generate color profiles. The calibration goal was a conventional sRGB display [3]: 120 cd/m^2 maximum luminance, 2.2 gamma, and D65 white point. Five CCKs were tested (Windows Display Color Calibration, X-Rite i1 Display Pro, X-Rite ColorMunki, DataColor Spyder4, and DataColor Spyder5).

Color Manager. The Windows Color Management, ColorMunki and Spyder4 ProfileChooser were tested with color profiles generated from different manufacturers.

Graphics Card Driver. The “Gamma” and “Digital Vibrance” settings in the nVidia graphics card driver software were tested.

Display Color Space. Three color spaces of the display (sRGB, Adobe RGB, and Native) were used to test the calibration capability of the CCKs.

Results

The key findings are summarized as follows.

WSI Review Software. Aperio ImageScope used a scanner color profile embedded in its proprietary .svs files. The RGB values will be altered if the “Image Color Management” option is enabled. Aperio ImageScope also altered the RGB values based on the display color profile assigned by the user. In other words, both Aperio ImageScope and Windows might alter the RGB values for the display if the color profile was not properly assigned. In contrast, Zeiss ZEN2 did not allow the user to choose the color profile. Instead, ZEN2 allowed the users to arbitrarily alter the RGB histograms, which can be saved in its proprietary .czi files. Nevertheless, previous study showed that the Zeiss device exhibited better color reproducibility than the Aperio device [4]. The output of WSI review software can be inspected with screen capture tools such as the Windows Snipping Tool, which reported the same RGB values as the Pixel Meter.

Color Calibration Kit. All five color calibration kits adjusted the gamma curve, maximum luminance, white point, and gray tracking only. The other display characteristics such as minimum luminance, color gamut, and color tracking were not calibrated. Windows Display Color Calibration was the only one that did not use an optical sensor but relied on visual judgment, so its calibration results deviated greatly from the others. For the same display, all four CCKs generated different calibration results, even the ones from the same manufacturers (Figure 2). Therefore, the so-claimed “calibrated displays” require a clearer definition and do not necessarily guarantee the identical color characteristics.

Color Manager. Theoretically the color profiles generated by all five CCKs should be standard and compatible with any color manager. However, we observed that Spyder4 and Spyder5 chose only the color profiles generated by themselves and overrode the Windows setting. In other words, when Windows showed that color profile *A* was in use, color profile *B* was actually effective. Such confusion could not be detected without using the pixel meter. Fighting between different color managers over color profile control might cause problems when deploying the new WSI modality to an existing, calibrated PACS environment.

Graphics Card Driver. We adjusted two settings in the nVidia driver and observed inconsistent behavior. The “Gamma” setting in the nVidia driver would be overridden by any subsequent color profile assignment. The “Digital Vibrance” setting, in contrast, would not be overridden by the color profile assignment and would impose additional color adjustment. In other words, the “Digital Vibrace” setting can throw off the color calibration suggested by the CCKs.

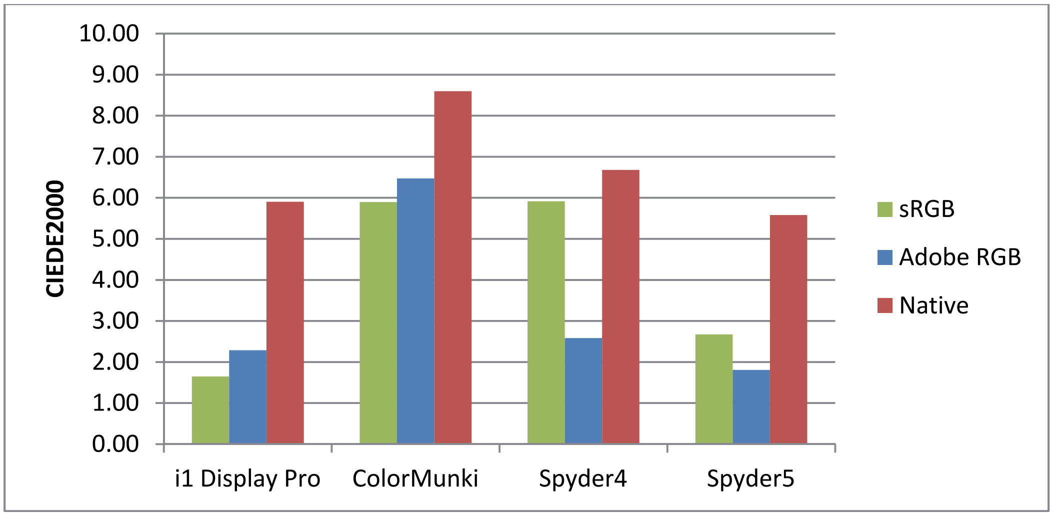

Figure 2: CIEDE2000 color differences introduced by various CCKs in various display color spaces. One unit of CIEDE2000 is equivalent to one just-noticeable difference in color [5].

Display Color Space. We used a pre-characterized, temporally stable display to compare the CCK sensor accuracy against a high-end spectroradiometer. The measurement results of maximum luminance show that i1 Display Pro and ColorMunki obtained identical results, while discrepancies between Spyder4 and Spyder5 were observed. In other words, the sensor accuracy might have contributed errors to the calibration. Figure 2 shows the mean CIEDE2000 color differences of the 140 color patches between before- and after-calibration done by four CCKs with respect to three various display color spaces.

New or breakthrough work

A novel method of measuring the digital RGB pixel values transmitted from the computer to the display was introduced so that the end user can inspect and verify the outcome of the color management. Unlike optical measurements obtained from a spectroradiometer or colorimeter, this method allows fast and repeatable measurements of the color management system in the digital domain. This method was used to detect unexpected behavior when various components from different manufacturers were mixed-and-matched in the color management system.

Conclusions

The display device is usually perceived as an independent, swappable component, and the importance of the computer environment is frequently overlooked. This study shows the tight coupling between the computer environment and the color display and demonstrates the entanglement between various color management components. Besides advocating the standardization, compatibility, and transparency of color management components offered by different vendors, incorporating a QA/QC tool such as the pixel meter can help avoid mishandling color management settings by the end user.

References

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Submitted for publication or presentation elsewhere

This work has not been submitted for publication or presentation elsewhere.