GreenVis: Energy-Saving Color Schemes for Sequential Data Visualization on OLED Displays

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ABSTRACT
The organic light emitting diode (OLED) display has recently become popular in the consumer electronics market. Compared with current LCD display technology, OLED is an emerging display technology that emits light by the pixels themselves and does not need an external back light as the illumination source. In this paper, we offer an approach to reduce power consumption on OLED displays for sequential data visualization. First, we create a multi-objective optimization approach to find the most energy-saving color schemes for given visual perception difference levels. Second, we apply the model in two situations: pre-designed color schemes and auto generated color schemes. Third, our experiment results show that the energy-saving sequential color schemes can reduce power consumption by 17.2% for pre-designed color schemes. For auto-generated color schemes, it can save 21.9% of energy in comparison to a reference color scheme for sequential data.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*screen design*

General Terms
Measurement, Performance, Human Factors

Keywords
OLED Display, Energy Saving, Optimization, Color Scheme, Visualization

1. INTRODUCTION
The organic light-emitting diode (OLED) display is an emerging display technology. It has recently entered the mobile and TV markets. For example, some new smartphones and tablets have OLED displays, including Samsung Galaxy S II [17] and Galaxy Tab 7.7 [18]. Large OLED TVs will also be available soon. For instance, LG plans to release a 55-inch OLED TV panel at CES 2012 [14]. Because of its beneficial properties, OLED displays may become the mainstream display technology in the future.

The OLED display technology has the following features: First, each pixel of an OLED display emits three channels of the color - red, green and blue. Second, because of the spectrum feature, the luminance of these three colors are different. For example, the black color is totally black - it does not emit light. And the white color has the maximum luminance because it fully combines the luminance of the three channels. Thus, the power consumption of an OLED display is directly related to the color displayed [8]. Dong et al. present a power consumption model for OLED displays and proposes an energy saving GUI design for smartphones [8].

As computer display screen sizes have increased over time, the display has become a major power-hungry device. Typically, over 38% of the power of a PC is consumed by the display [15]. Despite power efficiency approaches on mobile devices, the display power consumption is still up to 50% of the total power consumption [8]. As discussed previously, displayed colors can influence the power consumption of OLED displays. Thus, for visualization tasks, changing the color encoding can be an approach to save energy on power-hungry display devices.

In visualization, colors can be used to visually encode data. Brewer et al. present perceptually effective pre-designed color schemes for map visualizations [5]. They divide the color schemes into three types based on the types of data: sequential, diverging and qualitative. Wijffelaars et al. present an automatic method to generate color schemes. The rainbow color scheme is also widely used in visualization for these three types of data, despite its drawbacks for visual perception [3] [16]. Healey presents a method to choose named colors for data visualization [12]. In this paper, we focus on color schemes for sequential data in visualization.

Given the relationship between the power consumption of an OLED display and the color it is displaying, the natural question that arises is whether we can find energy-saving color schemes for visualization on OLED displays. And if so, how to manage the trade-offs between the effective visualization display and the power consumption?

In this paper, we discuss this problem in detail and present a

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multi-objective optimization approach to solve this problem. The contributions of our work are:

1. Based on the OLED power model, we build a multi-objective optimization approach to find energy-saving sequential color schemes for visualization based on visual perception difference levels.

2. We apply this model in two situations: pre-designed color schemes, and auto-generated color schemes.

3. Our experiment results show that the energy-saving sequential color scheme can reduce power consumption by 17.2% in pre-designed color schemes, and by 21.9% for auto-generated color schemes in comparison to the reference color scheme.

The rest of this paper is organized as follows: Section 2 discusses the background and related work on the OLED display power model, color space, color scheme and energy-saving visualization. Section 3 presents our general multi-objective optimization model and discusses how to apply our approach in two situations: pre-designed color schemes and auto-generated color schemes. Section 4 addresses the design of experiments to evaluate our model. The experiment results are presented in Section 5. In the Section 6, we discuss how to generalize our optimization model. And the last section summarizes the conclusions and future work.

2. BACKGROUND AND RELATED WORK

In this section, we provide an overview of the OLED display power model, color spaces, color schemes and energy-saving visualization. We do not discuss the mechanism of the OLED display technology in detail, but refer readers to existing references [10] [19].

2.1 OLED Display Power Model

Compared to current LCD displays, the organic light emitting diode (OLED) is an emerging display technology that emits light by the pixels themselves and does not need an external back light as the illumination source [8] [10] [19]. It is speculated that OLED displays will replace LCD displays as the mainstream in the future.

On OLED displays, there are three independent light emitting components with red, green and blue colors in each pixel. And these three basic colors have different luminance. Hence, the power consumption of OLED displays is directly related to the colors being displayed. Dong et al. give a power consumption model of OLED displays on the pixel level [8]. The power consumption of each pixel can be described as Equation (1).

$$P_{pixel} = f(pixel.R) + h(pixel.G) + k(pixel.B) \tag{1}$$

where $pixel.R$, $pixel.G$, $pixel.B$ present the color levels in the three basic color channels, and f, h, k are the respective power functions which are empirically modeled by experiments on each color channel.

Equation (2) presents the power consumption of the whole OLED display at the pixel level.

$$P_{screen} = P_{background} + \sum_{i \in Set(pixel)} P_{pixel_i} \tag{2}$$

where P_{screen} is the power consumption of the whole OLED display. $P_{background}$ is the background power consumption of the OLED display, and is tested while displaying a solid black screen. P_{pixel_i} is the power consumption of the calculated in Equation (1). The $Set(pixel)$ indicates the color information of each pixel on the OLED display. In addition, Dong et al. apply this power model to estimate the power consumption of the displayed image and find an energy-saving GUI style design [8].

2.2 Color Space

In data visualization, color can be used to present at least one dimension of the data. There are numerous representations of color space: RGB, HSV, CIELAB, CIELUV, etc. These color spaces are divided into two types:

- One type of color space is based on dispay device technologies, like the RGB color space. The color space represents all the possible combinations of the red, green and blue color channels.

- Another type of color space is based on visual perception - the CIE color space, for example, CIELAB and CIELUV [9]. In this type of the color space, the Euler distance of two colors has linear relationship with the visual perception distance.

Wijffelaars et al. shows the relationship between the CIE color spaces and the displayable color spaces [23]. Through that, we can see that the displayable color space is an irregular space. In order to display the CIE color space on a display device, we must transform the color from CIE color space to RGB color space. Ford et al. provide the manual for conversion between the different color spaces [9].

2.3 Data Types and Color Schemes

Regarding data types for information visualization, Ware divides data into four types: nominal, ordinal, internal and ratio [21]. Brewer et al. gives a taxonomy of color schemes for different data types in map visualizations as follows [11]:

- *Sequential*: The data is ordered, and it uses lightness to present ordered data. Darker colors are used for high-value data and lighter colors show the low-value data. No color in the scheme is more important than the rest, and all the colors in the scheme can be distinguished by user.

- *Diverging*: There is one neutral status in diverging data, and this neutral status is the midpoint which is encoded as the light color. The diverging sequences increase in darkness of different hues.

- *Qualitative*: There is no ordering of the data, and the different colors indicate the different clusterings.

Color in visualization can present at least one-dimensional information. However, choosing a color scheme for a visualization is not merely picking the pretty colors. If just choosing the favorite color, most people will choose blue [4]. There are several methods to generate color schemes for visualization. They can be divided into two types:

- *Pre-designed Color Schemes*: Brewer et al. offer ColorBrewer which has 3 types of 165 color schemes for map visualization based on their expert view [5]. Healey presented the named colors chosen by the color distance, linear operation and color category [12]. While the rainbow color scheme is also widely used in visualization, Borland et al. and Rogowitz et al. argue that the rainbow color scheme does not meet visual perception requirements and can lead to visual illusions [3] [16].
- *Auto Generated Color Schemes*: Zeileis and Hormik directly use the straight line and equal color distance in the CIELUV color space to generate color schemes [24]. Considering the color distance, Wijffelaars et al. present a method which uses beizer curves to simulate the ColorBrewer color schemes [23].

In this paper, we focus on sequential color schemes for visualization and apply our energy-saving model to both the pre-designed and auto-generated color schemes.

2.4 Energy-Saving Color Schemes

Our research is closely related to studies of energy-saving GUI design on OLED displays and energy-aware color sets on HDR displays. Dong et al. present their energy-saving GUIs and browser for OLED smartphones [8]. They report that their approach can reduce over 75% of display power consumption on smartphones. But, their approach for GUIs and browser design cannot generalize to visualization tasks and may offer poor usability. Chuang et al. present an energy-saving color-scheme generator method for the HDR display [7]. However, their approach can only be applied to the qualitative data type. The approach we present in this paper is a uniform energy-saving color model which focuses on sequential color schemes, but is also equally applicable to qualitative data coloring and diverging data coloring.

3. GREENVIS APPROACH

Our research question is to find energy-saving color schemes for visualization on OLED displays. In order to solve this problem, we must consider the primary factor that directly influences OLED power consumption, the color schemes. In addition, for given data, whether the different color schemes will offer effective perception of the data in the visualization is another factor which needs to be considered.

In our approach, the first factor is based on the *OLED display power model*. We define the second factor as the *visual perception difference level*. Visual perception difference level is a metric that measures the color distinction in the color scheme of the visualization from a perceptual point of view. It is a human-factors parameter. We will describe it in more detail in the following section.

3.1 GreenVis Power Model

Dong et al. [8] build the power model of OLED displays at the pixel level. At the same time, the encoding of data using colors in the visualization renders the different geometric regions in the visualization in different colors according to the color scheme. Based on their power model at the pixel level (Equation (1) and Equation (2)), we can easily derive the OLED power model at the region level. The region level power model uses each region's percentage of the whole screen and the color information to estimate the power consumption of the whole OLED display. The region-level power model can be described as in Equation (3).

$$P_{screen} = P_{background} + \frac{\sum_{i=1}^{N}(Area_i \times P_{Color_i})}{\sum_{i=1}^{N} Area_i} \quad (3)$$

where P_{screen} is the total power consumption of the visualization on the OLED display. $P_{background}$ is the power which is tested when the screen displays a solid black color. The whole screen can be divided into N regions of N distinct colors. Each $Region_i$ is the union of all pixels of $Color_i$ (regions are not necessarily contiguous). $Area_i$ is the area of $Region_i$ (in pixels) and $i \in [0, N-1]$. $Color_i$ is the color of the $Region_i$ in the color scheme CS. P_{Color_i} is the power consumption when the whole OLED screen displays $Color_i$. The goal is to find the N best colors for the color scheme.

For the given color scheme CS, we can first use the power consumption model Equation (1) for the each $Color_i \in CS$, then sort the color scheme CS in order to let $Power(Color_i) < Power(Color_j)$, where $Color_i$, $Color_j \in CS$ and $i < j$. For the sequential and diverging types of color schemes, the area of the $Region_i$ A_i does not need to be sorted. Because the ordering of the regions has been restricted by the data itself. In this paper, our scope does not focus on qualitative data. But in this model, for qualitative data, we need to sort A_i by descending ordering (let $A_i < A_j$ when $i > j$).

After building the power consumption estimate model, the next step is to optimize this model and find the most energy-saving color scheme for the visualization. The color encoding of the visualization is to enable the user to detect the different regions. Through Equation (1) and Equation (2), we can know that the dark colors save more energy. However, we need to choose colors which can be distinguished easily. We define the visual perception difference level to measure the color distinction in the color scheme for the visualization. Thus, there is a trade-off between the power consumption reduction and the visual perception difference level. The goal is to maximize the visual perception difference level and find the minimum power-consumption color scheme for the visualization. It can be described as the multi-objective optimization format in Equation (4).

$$\min \quad y = (P_{screen}, -\Phi_N) \quad (4)$$

where P_{screen} is the power consumption of whole OLED display, as in Equation (3). Φ_N is the visual perception difference level for the N regions in the visualization. In order to maximize Φ_N, it is described to minimize $-\Phi_N$.

This problem can be presented as optimizing the power consumption under a list of the specific visual perceptual difference levels Φ_N based on all N colors in the color scheme CS. The solutions of the multi-objective optimization problem can be described as a Pareto frontier [13].

In the $CIELAB$ and $CIELUV$ perceptual uniform color space, the visual perception difference level Φ_N can be normally considered as the Euler distance of any two colors of the N colors in the color scheme CS. For pre-designed color schemes, we cannot modify the value of Φ_N. It has been defined by the color scheme itself. However, for auto-generated color schemes, we need to adjust Φ_N for the optimization. Φ_N can be chosen based on metrics with regards to the type of data, as discussed in Section 3.3. We can control the value of Φ_N in order to get the most energy-saving color scheme for different visual perceptual difference levels. The power consumption of the energy-saving color scheme will be the Pareto frontier in the Power Consumption-Visual Perceptual Difference Level chart as Figure 4.

In our general model, the type of the color scheme is an important factor to influence power consumption estimation. We will discuss our model in detail for two situations: pre-designed color schemes, and auto-generated color schemes.

3.2 Pre-designed Color Schemes

There are some pre-designed color schemes, including ColorBrewer [11], Healey's color scheme [12] and the rainbow color scheme [3]. These pre-designed color schemes can be used for sequential, diverging and qualitative data visualization. In this paper, we focus on sequential data visualization. We use the sequential color scheme from ColorBrewer as an example to discuss how to apply our general model to sequential data visualization on pre-designed color schemes. In this situation, we cannot change the visual perception difference level Φ_N and the color ordering. In another words, Φ_N is fixed for the specific color scheme. Thus, the multi-objective problem is simplified to the single-objective optimization. To find the most energy saving color scheme in these pre-designed color schemes, the Equation (4) can be described as

$$min \quad y = P_{screen} \tag{5}$$

The optimization process is to apply each pre-designed color scheme CS into the Equation (5) and find the minimum power consumption color scheme.

3.3 Auto-Generated Color Schemes

For auto-generated color schemes, our model will have a larger search space for the optimization than for pre-designed color schemes. The visual perception difference level Φ_N can be varied in this type of color scheme.

There exist some auto-generated color schemes for sequential data visualization. Wijffelaars et al. give an approach that uses bezier curves to simulate ColorBrewer color schemes in $CIELCH_{uv}$ color space and automatically generate the sequential color scheme by the given intuitive parameters [23]. Alternatively, Zeileis and Hormik directly use the straight line and equal color distance in CIELUV color space to generate color schemes [23].

We choose Wijffelaars' single hue sequential color scheme generator approach as an example to apply our GreenVis general model. Its intuitive parameters are the Hue $H \in [0^\circ, 360^\circ]$, the Saturation $s \in [0,1]$, the Brightness $b \in [0,1]$ and the Contrast $c \in [0,1]$ [23].

At the same time, we also need to define the visual perception difference level Φ_N. Normally, Φ_N is the distance between colors in the perceptual uniform color space. For given specific data, we need to consider the data features to give the definition of the Φ_N . These are the requirements of the sequential data color scheme [22]:

- The colors should have a clear ordering in the perception.
- The visual perception difference level is related to the data difference linearly.
- The colors are equally important in the visual perception level.

Thus, we need to define the visual perception difference level Φ_N to meet these requirements. Wijffelaars et al. define the color distance of sequential color schemes in the $CIELCH_{uv}$ color space as Equation (6).

$$D(c_1, c_2) = |\ln(\frac{125 - c_1.L}{125 - c_2.L})| \tag{6}$$

where D is the color distance, c_1 and c_2 are any two colors, L is the lightness component of the color. Equation (6) means that the color distance is based only on the lightness component of the colors. For sequential data, the maximum distance will be the distance between the start color $Color_s$ and the end color $Color_e$ in the auto generated color scheme CS, as $D(Color_s, Color_e)$. Thus, in our model for sequential data visualization, we define Φ_N as the scaled value from 0 to 1 of $D(Color_s, Color_e)$.

In the optimization process, the free variables are H, s, b, and the number of the sequential parts N are given by user input. The Contrast c is directly related to the lightness component of colors. So, c is related to Φ_N. We need to control the value of Φ_N to apply to Equation (4) and find the most energy-saving sequential color scheme for the different values of Φ_N.

4. EXPERIMENTAL METHODOLOGY

In this section, we detail the experimental methodology and setup that we employ in our evaluation of the GreenVis model and the OLED display power model.

4.1 Experiment Settings

The OLED display device used in the experiment is μOLED-32028-P1 AMOLED display module from 4D System [1]. The measurement devices are Agilent 34410A multi-meter

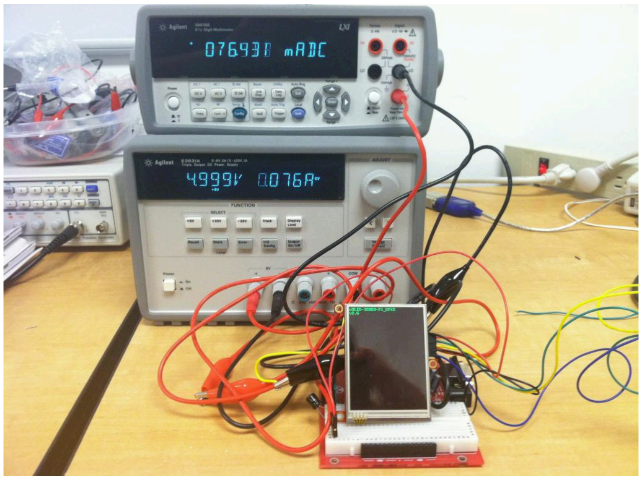


Figure 1: The experiment device settings for our evaluation

Table 1: 4D System μOLED-32028-P1 AMOLED Display Module Optical Characters

Chromaticity	Red	Green	Blue	White Point
CIE x	0.66	0.29	0.15	0.31
CIE y	0.33	0.66	0.16	0.33

and Agilent E3631A DC power supply. The OLED display module is 320×240 resolution with $65K$ colors. Figure 1 shows the experiment hardware settings. During the measurement, we set the DC voltage to 5.0V and track the electrical current values in order to calculate the power consumption by $P = UI$.

The optical characters of the μOLED-32028-P1 AMOLED display module is listed in Table 1. Using the parameters CIE x and CIE y in Table 1, we can get the forward transformation matrix M from RGB to CIEXYZ and the reverse transformation matrix M^{-1} from CIEXYZ to RGB [9]. We need to mention that the RGB color space here is specific for μOLED-32028-P1 AMOLED display module. Thus, the same RGB values in our OLED display and sRGB present different colors in CIEXYZ color space.

4.2 OLED Display Power Model Evaluation

In order to verify the power model from Dong et al. [8] on our OLED display module, we display three color channels and three blended colors in the whole OLED display individually. The six test color channels are R-red, G-green, B-blue, Y-yellow (red + green), M-magenta (red + blue) and C-cyan (green + blue). The color level is scaled from 0 to 31. Thus, we need to test 192 (32×6) different colors. And for each color, the test lasts for 10 seconds. The multimeter records the current value every second. The current value of each color is the average of its 10 records.

4.3 Treemap

We use a treemap as the example of visualization for our evaluation. Treemaps are one type of visualization for hierarchical data [2]. It uses recursive space filling to present the tree data structure. In treemaps, colors can indicate one dimension of the data [6]. The reason why we use treemaps as the evaluation example is that treemaps have high data density and fill the space efficiently. An important difference between treemaps and other visualization approaches is that the treemaps do not need a background color because they are space filling. The colors in the space are only related to the data itself. The area of the color filling is the unique factor in our model.

The treemap we use for the evaluation is generated by a random binary tree. It has 59 leaf nodes and the area of each node is the same. For each leaf node, we assign a random integer value from 0 to 8 as the sequential data label for coloring. The treemap we use for evaluation is shown in Figure 2 (a).

4.4 Experiments on Color Schemes

For the pre-designed color scheme, we apply our model on all the 9-levels sequential color schemes in ColorBrewer for the treemap visualization. Then, the energy saving color scheme is chosen by our model and the power consumption is estimated. At the same time, the rest of the sequential 9-levels color schemes in ColorBrewer are applied on the same treemap as the reference group.

For the auto-generated color scheme, we choose Wijffelaars' approach [23] to generate 9-level sequential color schemes for the treemap visualization. As in the description of Equation (4) and the discussion in Section 3.3, we can use the multi-objective optimization approach to find the most energy-saving color scheme for various values of visual perception difference level Φ_9. In the optimization process, we set the visual perception difference level Φ_9 as 0.2, 0.4, 0.6, 0.8, 1.0 and search in the space: $\{hue | 0 \leq hue \leq 360, hue \in \mathbb{Z}\} \times \{saturation | 0 \leq saturation \leq 1\} \times \{brightness | 0 \leq brightness \leq 1\}$ for the energy-saving color schemes. The set of energy-saving color schemes for different Φ_9 can be described as the Pareto frontier. At the same time, we use the gray scale sequential color scheme in the same visual perception difference level as the reference group to compare against.

5. EXPERIMENTAL RESULTS

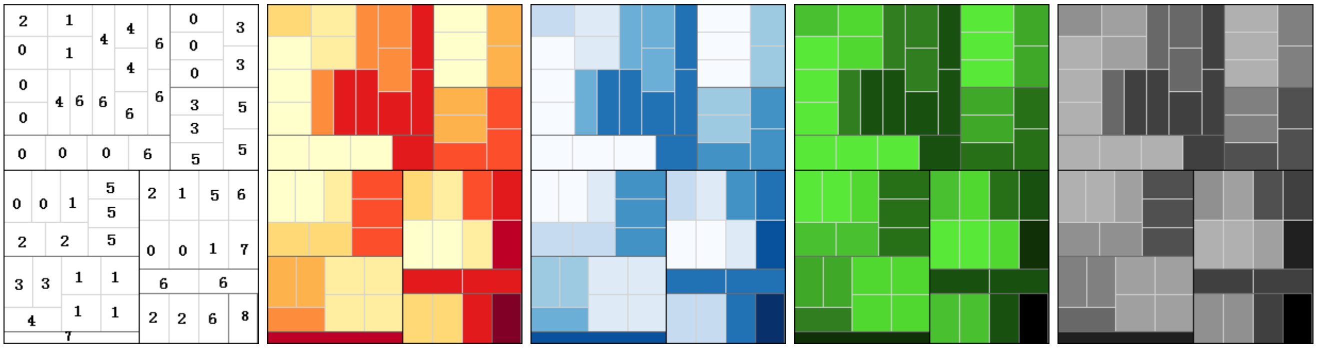
In this section, we present our experimental results from the measurement of the power consumption in three experiments that are described in Section 4.

5.1 OLED Display Power Model Evaluation

The experimental results of the OLED display power model are plotted in Figure 3. The X-axis indicates the scale of the color level from 0 to 31. The Y-axis presents the power consumption. We can see that the curves are nonlinear which is an effect of the gamma correction [8]. The experiment results shows that our OLED display module follows the power model in Equation (1) and Equation (2). Through the results, we can also see that $P_{background}$ of our OLED display module is 0.36 W.

5.2 Pre-designed Color Scheme

For the pre-designed color scheme evaluation, the treemap visualization results are shown in Figure 2 (b) and Figure 2



(a) (b) (c) (d) (e)

Figure 2: Treemap Visualization Results. (a) Treemap visualization for our evaluation (b) Most energy saving sequential color scheme from ColorBrewer (c) Most energy consuming sequential color scheme from ColorBrewer (d) Energy saving color scheme in $\Phi_9 = 0.6$ (e) Reference color scheme in $\Phi_9 = 0.6$

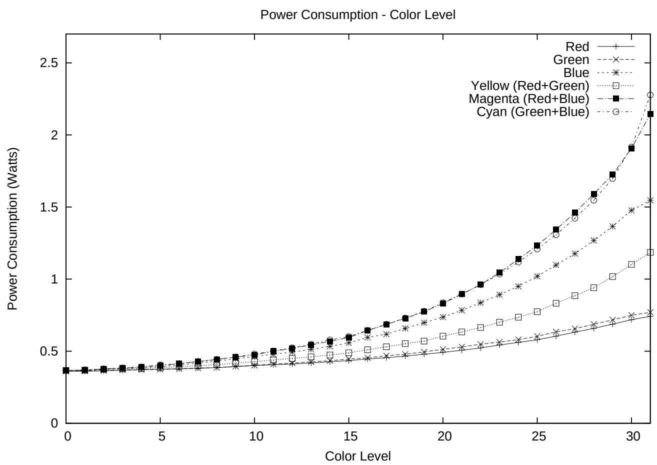


Figure 3: Experiment results of the OLED display power model

Table 2: Results of Pre-designed Color Scheme (Watts)

Most Energy Saving	Average	Most Energy Costing
1.171	1.414	1.625

(c). Figure 2 (b) shows the most energy-saving 9-level sequential color scheme from ColorBrewer. At the same time, the treemap with the most energy-consuming color scheme is in Figure 2 (c). Table 2 shows the power consumptions of the most energy-saving color scheme, the average of the reference color schemes, and the most energy consuming color scheme. Compared with the average power consumption of the reference color schemes, we can see that the most energy-saving color scheme saves 17.2% of energy.

5.3 Auto Generated Color Scheme

The experiment results are shown in the Figure 4. From the results, we find that the sequential energy-saving color scheme can reduce 21.9% of power consumption on average over the reference color scheme. The set of the energy-saving color schemes in the different values of Φ_9 assembles the Pareto frontier of this multi-objective optimization. The treemap visualization with the most energy-saving sequential color scheme with $\Phi_9 = 0.6$ is shown in Figure 2 (d). Figure 2 (e) shows the visualization result using the greyscale reference color scheme in $\Phi_9 = 0.6$. We also list the *CIELUV* parameters of the color schemes in Figure 2 (d) and (e) as Table 3 (a) and (b) respectively.

Table 3: Energy-Saving Auto Generated Color Scheme

(a) Energy-Saving Color Scheme ($\Phi_9 = 0.6$)

	0	1	2	3	4	5	6	7	8
L	78	71	64	57	48	38	27	14	0
u	-68	-62	-56	-50	-42	-33	-23	-13	0
v	100	92	83	73	62	49	35	18	0

(b) Reference Color Scheme - Gray Scale ($\Phi_9 = 0.6$)

	0	1	2	3	4	5	6	7	8
L	95	89	82	73	63	52	37	20	0
u	0	0	0	0	0	0	0	0	0
v	0	0	0	0	0	0	0	0	0

6. DISCUSSION

In this section, we discuss generalizations of our GreenVis approach.

6.1 Generalize to all parts of a visualization

The visual encoding is just one part of an information visualization. A complete information visualization application also includes the background color, labels, legend, caption and text [20]. These parts must also be considered in order to reduce the total power consumption.

For many visualizations, the background might be the largest area displayed, and usually in a single solid color. Through the OLED display energy model in Section 2.1, we know that a black colored background will reduce the most power consumption. The reason is that OLED displays do not emit any light from pixels that are colored fully black. So, a simple first step is to adjust the background to the color black. For text labels, using a white color text will achieve high contrast with the black background color. Because text likely

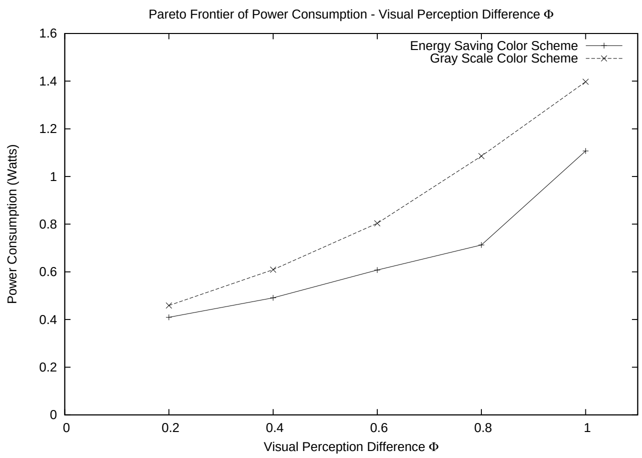


Figure 4: Multi-objective optimization results for the auto-generated color scheme

consumes a relatively small total number of pixels, the high power cost of white color is acceptable. After these initial steps, we can then begin our approach described in the previous sections. However, we will need to reduce our search space of the optimization so that the user can distinguish between the color-encoded data and the black background color (and possibly also the text color, depending on the layout). In this step, we can also use the visual perception difference level Φ_N to measure the difference between the color schemes and the color of the background.

6.2 Generalize to diverging and qualitative data

In the above sections, we discussed how to apply our GreenVis model to an auto-generated color scheme for sequential data visualization. Now, we discuss two other data types - diverging and qualitative data. For diverging data, we can also apply our model. However, the visual perception difference level Φ_N will need to be re-defined. For diverging data, Φ_N is the sum of the color distance between the two end colors and the midpoint color. For qualitative data, Chuang et al. present an energy-saving auto-generated color scheme approach [7]. In their model, they fix the lightness value and search for colors with the same visual perception difference level on the same lightness surface of the CIELAB color space. Whereras, in our model, we do not need to restrict the lightness value to a constant. Based on our multi-objective optimization model, we can find energy saving color schemes using the whole color space.

7. CONCLUSION AND FUTURE WORK

In this paper, we present our approach to reduce the power consumption on OLED displays for sequential data visualization. First, based on the OLED power model, we build a multi-objective optimization approach to find the most energy-saving color scheme based on the visual perception difference level for visualization. Second, we discuss the model in the two situations: pre-designed color schemes, and auto-generated color schemes. For pre-designed color schemes, the visual perception difference level is defined by the color scheme itself, and the model becomes a single-objective optimization. We apply our model to ColorBrewer, an expert-generated color scheme for map coloring. For the auto-generated color schemes, we apply our model to Wijffelaars' color method to generate energy-saving color schemes based on the visual perception difference level for sequential data. Finally, we evaluate our approach on a treemap visualization. The experiment results show that the energy-saving color scheme we choose can reduce power consumption by 17.2% in ColorBrewer. In the auto-generated color scheme, it can save 21.9% of power in comparison to a gray scale as the reference color scheme for sequential data.

In the future, we plan to apply our approach to diverging and qualitative data visualization and build a general evaluation framework for the visual perception difference level of the energy-saving color schemes.

8. ACKNOWLEDGMENTS

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