A Tool for Stereoscopic Parameter Setting Based on Geometric Perceived Depth Percentage

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***Abstract*—It is a necessary but challenging task for creative producers to have an idea how the target audience might perceive when watching a stereoscopic film in a cinema during production. This paper proposes a novel metric, geometric perceived depth percentage (GPDP), to numerate and depict the depth perception of a scene before rendering. In addition to the geometric relationship between the object depth and focal distance, GPDP takes the screen width and viewing distance into account. As a result, it provides a more intuitive mean for predicting stereoscopy and is universal across different viewing conditions. Based on GPDP, we design a practical tool to visualize the stereoscopic perception without the need of any 3D device or special environment. The tool utilizes the stereoscopic comfort volume, GPDP-based shading schemes, depth perception markers, and GPDP histograms as visual cues so that animators can set stereoscopic parameters more easily. The tool is easily implemented into any modern rendering pipeline, including interactive Autodesk Maya and off-line Pixar's RenderMan renderer. It has been used in several production projects including commercial ones. Finally, two user studies show that GPDP is a proper depth perception indicator and the proposed tool can make the stereoscopic parameter setting process more easy and efficient.**

***Index Terms*—Geometric perceived depth percentage (GPDP), Stereoscopic visualization, Stereoscopic manipulation.**

I. Introduction

Recently, stereoscopic contents become more and more popular, especially in cinemas. However, badly-set stereoscopic effects generally make the audience feel fatigue and sick while watching. This is definitely not production intention. In order to produce comfortable stereoscopic effects for 3D animations, it generally requires several iterations of stereoscopic parameter setting and reviewing, consisting of a manual stereoscopic parameter setting process, a stereoscopic rendering procedure, and a reviewing session on special stereoscopic equipment. Because rendering is time-consuming, it would be helpful to have an indication on how the target audience might perceive before actually rendering the content out. This paper proposes a novel metric and an intuitive tool so that animators can visualize and foresee the depth effects without rendering 3D contents and using stereoscopic equipment, effectively reducing the number of reviewing iterations and shortening the time for stereoscopic parameter setting.

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The effective control of the perceived depth is the key to a successful production. Although there are guidelines for producing comfortable stereoscopic effects [1], [2], they can only act as guidance and cannot help set stereoscopic parameters directly. There are also stereoscopic perceptual metrics proposed from psychophysiological aspects [3], [4], [5], [6]. However, they can be only used for production evaluation but are not quite effective for the parameter setting process. Although a depth map can reveal the distances of characters/objects to the camera, the depth cannot directly reflect the depth perception and strength of stereoscopic effects because it does not take the camera parameters and the screening environment into consideration. Parallax and disparity are another two available metrics. They however heavily depend on the 3D screening environment; and the same 3D content can deliver very different 3D watching experiences when the 3D screening condition changes. Because depth interpretation is device-dependent, these metrics cannot be directly used as an auxiliary stereoscopic setting tool. Additionally, parallax falls short in providing intuitive control for the desired stereoscopic effects. Because depth perception is relative, we address these issues by proposing a novel metric, geometric perceived depth percentage (GPDP), using the relative ratio of perceived depth to the screen distance to extend binocular disparity with consideration of the screen width and viewing distance. As shown in Fig. 1, it is important to have proper indication of stereoscopic perception during production and to our best knowledge, there is no other stereoscopic setting tool available publicly. Our proposed GPDP can provide a more intuitive depth-perception indicator and gets rid of the issue with different 3D experiences when watching with different displays.

It is common to evaluate stereoscopic effects using 3D display facilities, such as 3D monitors, 3D projectors, autostereoscopic displays, and head-mounted displays. The need to use stereoscopic displays often interrupts the parameter tuning process. In addition, these displays often cannot provide a faithful 3D watching experience similar to what the target audience might have. For examples, 3D animations are often made for screening in a cinema. It is however very unlikely to review the 3D contents under production in a cinema. Viewing them on other stereoscopic displays often provides a wrong indication to the experience in the cinema because of very different stereoscopic settings. The proposed GPDP addresses this issue by considering the stereoscopic setting. Furthermore,

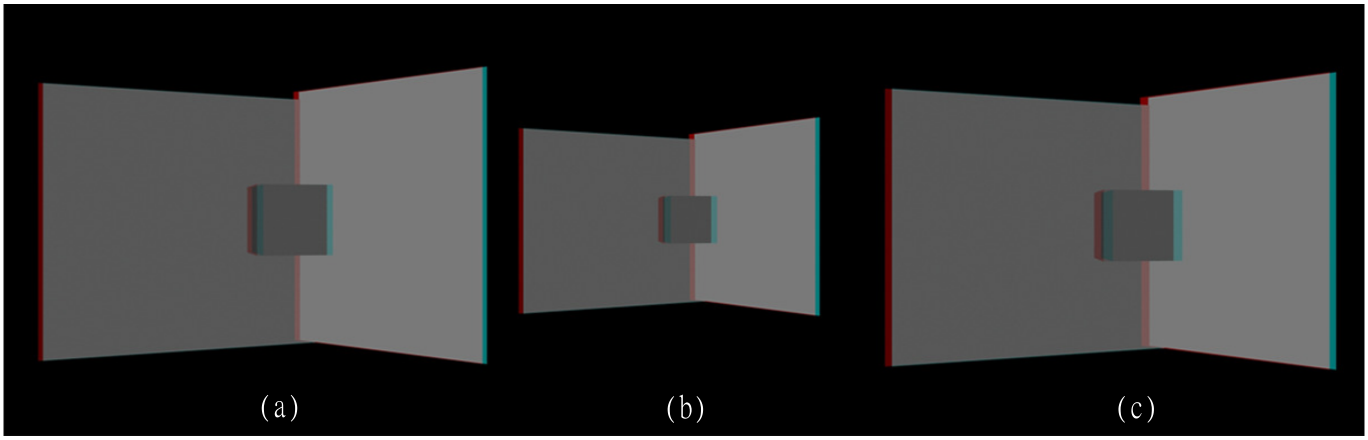


Fig. 1. (a), (b) and (c) show the stereoscopic results of a scene rendered with (I_s, Z_p) equal to $(0.461, 30.0)$, $(0.692, 30.0)$, and $(0.692, 30.0)$ respectively. (b) simulates editing scenes in a 27-inch monitor, and (a) and (c) simulate displaying results in a 40-inch device. All images are shown in anaglyph format by maintaining their relative screen-size ratio. Traditionally, when adjusting stereoscopic parameters, animation production tools, such as Maya, provide a disparity-based auxiliary tool to visualize the editing scene in corresponding stereoscopic view as (b) but the view is different from the one shown in a cinema (e.g., (c) is rendered with the same stereoscopic parameters for a different screen size. Actually, (a) is the desired stereoscopic result for maintenance of depth perception. It is important to have a tool for helping animators interpret the audience depth perception. To our best knowledge, there is no other stereoscopic setting tool available publicly.

it can be used with a color scheme to shade a 3D scene for visualizing possible depth perception without the need of specific equipment, and easing the parameter setting process. The color schemes and style of visualization are carefully chosen for constructing the depth-perception metaphor easily. When incorporating with a set of GPDP marker planes to illustrate the possible stereoscopic volume, the proposed tool can make the stereoscopic parameter setting process more efficient. The proposed tool can be implemented and integrated into the modern animation pipeline easily to display the possible depth perception immediately.

We have implemented the proposed tool into interactive Autodesk Maya and off-line Pixar RenderMan. The tool has been used for making a few academic feature animations and a few commercial animations by a production house. In addition, two user studies were conducted to verify the effectiveness of GPDP across different screen sizes and the usefulness of the proposed tool. The results show that GPDP is effective in indicating the possible depth perception of the audience and the proposed tool can help animators efficiently and accurately set up stereoscopic parameters. In summary, this paper proposes a practical solution to depict depth perception of 3D contents in a cinema through a novel metric and proper visualization for facilitating the stereoscopic setting process. This paper makes the following contributions:

1) We propose a practical and generic metric, geometric perceptual depth percentage (GPDP), for depicting depth perception. The metric considers viewing conditions and provides a unified indication to stereoscopic viewing experience on different stereoscopic viewing settings.
2) Based on GPDP, we implemented a visualization and manipulation tool for facilitating the stereoscopic parameter setting process. The tool uses GPDP maker planes, GPDP-based shading schemes, and GPDP histograms as visual cues for depicting depth perception. With these cues, animators can set the parameters more efficiently without using any stereoscopic display.

The following of the paper is organized as follows: Section II reviews previous work related to this work. Section III introduces the proposed GPDP metric. Section IV explains the proposed visualization and manipulation tool for stereoscopic parameter setting. Section V describes our implementation and its use in production. Section VI discusses the user studies for verifying the effectiveness of GPDP and the usefulness of our tool. Section VII concludes with a discussion of limitations and future work.

II. Related work

Stereoscopy is a multi-disciplinary field involving binocular vision and perception, camera and display technologies, as well as cinematography and art. Here, we only discuss work directly related to our work. Readers who would like to learn more about this field can refer to books of the subject, such as the one by Su *et al.* [7].

3D Devices. There are already a large number of 3D display devices on the market, including binocular displays, multi-view displays, integral imaging displays, volumetric displays and holographic displays [8]. Among them, binocular displays are the most popular in production houses because they are easy to adopt, natural to human eyes, and most importantly in a similar watching style as a stereoscopic theater. Because of many manufacturing factors, these displays could have quite different characteristics even for displays within the same category. Our GPDP is designed to consider different viewing conditions.

Stereo geometry and perception. The human visual system can estimate the distance, depth, and scale through a large number of visual cues [8], [9]; among them, occlusion, motion parallax, and stereo disparity (or binocular disparity) have more contributions on depth perception than others when the viewing distance is short. The geometrical models of binocular vision for explanation and prediction of depth perception and binocular distortion have been studied extensively [3], [4], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]. Some show the connection between the vergence-accommodation conflict and the stereoscopic discomfort and define a comfortable 3D view volume in front of eyes [10], [19], [26]. In addition, there are a few empirical rules for depth perception learned from experiences in the S3D film industry [1], [2]. Generally, the factors of stereoscopic discomfort are nonlinear and difficult to translate into a simple metric. GPDP is a geometric metric which can implicitly reflect the possible depth perception and can be used for intuitive control for stereoscopic parameters. Additionally, a color scheme is chosen to shade the surfaces with GPDP to reflect the depth perception by means of colors and a stereoscopic histogram reflects the relative depth motion and the amount of stereoscopy within a shot.

There are psychophysical metrics that can be used for evaluating the performance of stereoscopic images and animations [3], [4], [5], [6], [21], [23], [25], [27], [28], [29], [30], [31], [32]. Each metric considers a set of factors such as stereo contrast ratio, luminance contrast, disparity, motion in depth, motion on the screen plane, the spatial frequency of luminance contrast, vertical misalignment, viewing time, and stereo fusion range. Although these metrics can evaluate the psychophysical perception of a stereoscopic animation, they require rendering of the content. Even worse, they are not intuitive. Our goal is to give an intuitive indicator without the need of time-consuming rendering.

Stereoscopic content analysis and post-processing. Based on analysis of stereo geometry, several researches [33], [34], [35] analyze the stereoscopic characteristics of videos for the prediction and correction of visual distortions such as cardboarding. Disparity control is important for creating high-quality stereoscopic images and videos. Some proposed to confine the scene content within the stereoscopic comfort zone for more comfortable watching [14], [19]. Lang *et al.*proposed a set of nonlinear disparity remapping operators to adjust depth perception of existing 3D contents [36]. A detailed state-of-the-art report on stereoscopic post-production is provided by Smolic *et al.* [37]. These methods mainly aim at recovering disparity from the input images/videos and manipulating them with image-based or warping-based methods. They only take the disparity into consideration but not the viewing and screening conditions.

III. Geometric Perceived Depth Percentage

For the vast majority of adults, eyes are horizontally separated about 50-75*mm* denoted as the interocular distance [38]. Binocular disparity refers to the difference

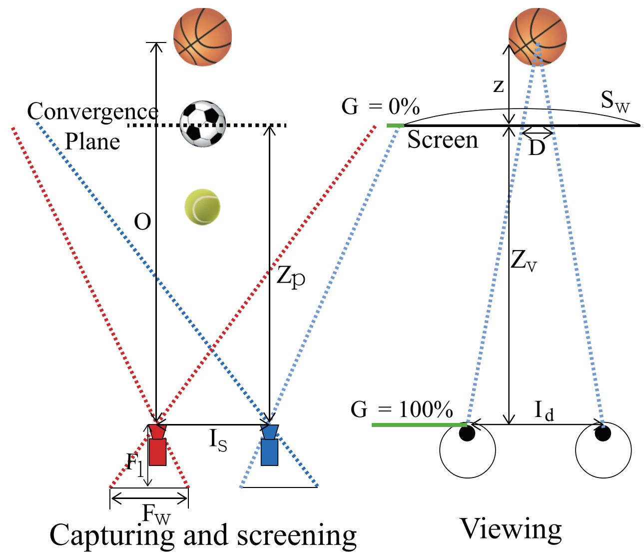


Fig. 2. The geometric relationship of stereoscopy for capturing, screening, and viewing. The left shows the capturing and screening processes. Two cameras with a focal distance F_l and a film width F_w, separated with a distance I_s capture an object at a distance of O. The convergence plane for screening is set at a distance of Z_p. The right shows viewing stereoscopic contents on a screen. The interocular distance of the viewer is I_d and the viewing distance is Z_v. The object perceived is located at a relative depth of Z with a screen disparity D from two views.

between the image locations of an object seen by the left and right views. There are two types of disparity: one is the image disparity with the unit of pixels; while the other is the display disparity, measured on the display screen with the unit of centimeters. The display disparity is perceived by the brain to extract depth information from the two-dimensional retinal images for stereopsis. In stereoscopic 3D film production, stereopsis generation is related to three steps: capturing, screening and viewing; and each has different effects on the binocular disparity. We will discuss the effects related to these steps in the following. For capturing or synthesizing stereoscopic contents, there are two stereoscopic camera configurations: off-axis and toe-in. The off-axis configuration shown in Fig. 2 is a more popular choice for synthesizing contents because it is more convenient for configuring transitions and adjusting transformations. In this configuration, there are two commonly used stereoscopic parameters, I_s and Z_p, where I_s is the interaxial separation of the left and right cameras and Z_p is the distance from the mid-point of the left and right cameras to the convergence plane whose binocular disparity is zero. Additionally, animators generally assume coincidence of the convergence plane and the display screen. Animators adjust Z_p to adjust the location of the convergence plane. If the convergence plane is moved toward the camera (i.e., Z_p decreases), the degree of popping out decreases because all characters/objects are moved toward the back of the screen. Effectively, the strength of stereoscopic perception decreases. On the contrary, if the convergence plane is moved away from the camera (i.e., Z_p increases), the degree of popping out increases because all characters/objects are

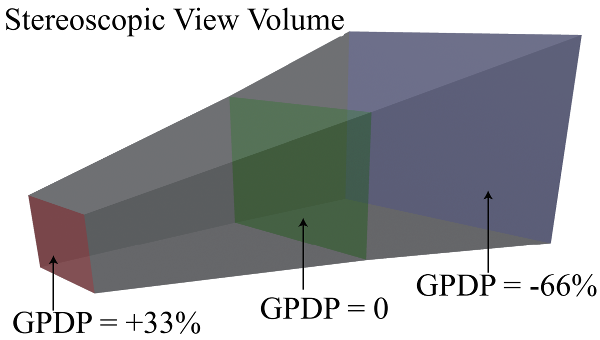


Fig. 3. The stereoscopic comfort volume bounded by the far (blue) and near (red) planes in the GPDP space defined by Eq. 4. As an empirical rule, the far plane is defined as the one whose GPDP is -66% and the near plane with GPDP as 33%. The green plane indicates the convergence plane whose GPDP is zero.

moved forward. As a result, the strength of stereoscopic perception increases. Animators adjust I_s to tune the distance between the left and right cameras and it affects the size of the stereoscopic volume i.e., the physical size of the comfort zone as the one shown in Fig. 3. Increasing I_s moves the nearest and farthest planes closer to the convergence plane and shrinks the stereoscopic volume, and thus it enhances the strength of stereoscopic perception. On the other hand, decreasing I_s moves the nearest and farthest planes away from the convergence plane and enlarges the stereoscopic volume, and it effectively reduces the strength of stereoscopic perception. To present the desired stereoscopic perception to the audience, it is required to set these parameters properly. Traditionally, the setting process depends on animators' experiences with little help from built-in disparity-based tools and 3D devices to guess the possible depth perception in a cinema as shown in Fig. 1. To have auxiliary tools can help them predict stereoscopic perception, but to our best knowledge, there is still no setting tool available publicly.

In order to describe the goodness of these stereoscopic parameters, it is essential to define a metric for predicting stereoscopic perception for a given configuration of stereoscopic parameters. One such metric is parallax, P, which considers solely the capturing aspects and is defined as [22]

$$P(x,y) = \frac{F_l}{F_w}\left(\frac{I_s}{Z_p} - \frac{I_s}{O}\right), \tag{1}$$

where (x,y) is the image plane coordinate, O is the object distance from the point of an object to the camera, F_l is the focal length of the camera, and F_w is the film width. Conceptually, parallax represents the percentage of movement between the projected locations of a character/object in the left and right views relative to the film width. A main shortcoming of parallax is that it completely ignores the screening configuration. The parallax is the same no matter which display is used. However, the strength of stereoscopic perception is highly related to the display size. In general, the larger the device is, the stronger the strength is. Furthermore, it is difficult for animators to adjust per-pixel parallaxes to achieve the desired stereoscopic performance required by the director.

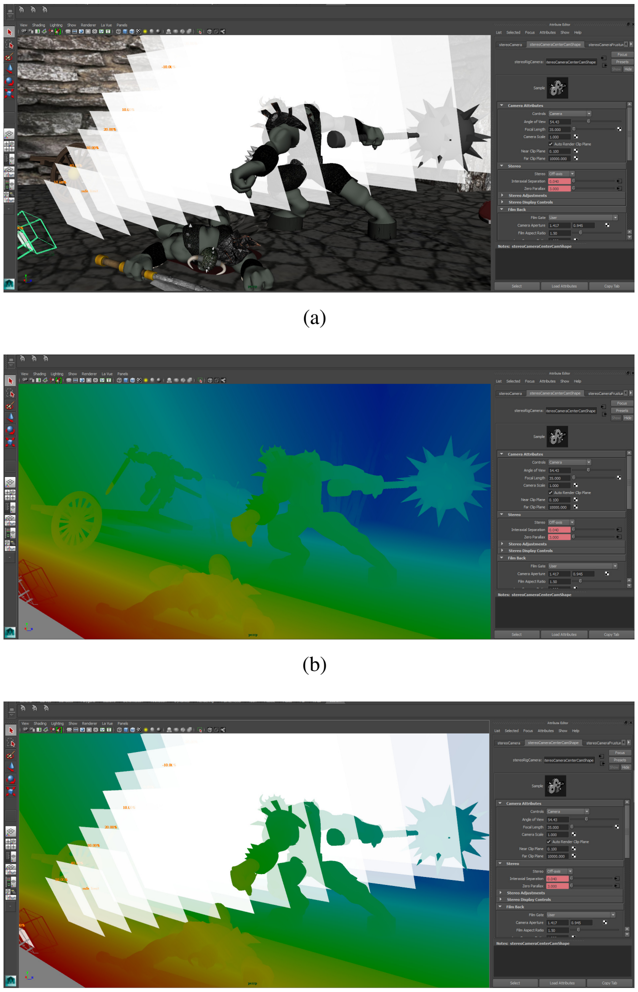
In order to take the screening condition into consideration, disparity, D, is introduced to consider both aspects in capturing and screening with the factor of the screen size and can be computed as

$$D(x,y) = \big(P(x,y) + T_{off}\big)\, S_w, \tag{2}$$

where S_w is the screen width and T_{off} denotes the offset between the projected left and right images in percentage relative to the screen width. In most cases, T_{off} is 0, which means the projected left and right images are aligned on the screen. However, in some IMAX theaters, there is a 1% offset. It is used to create a deeper and more immersive experience which is called IMAX experience. In other words, the parallax of a pixel multiplied with the screen width gives the disparity which represents the actual displacement of the projections of a point on the screen with a real-world unit for length, such as *cm*. A negative disparity represents that the object is perceived as popping out of the screen and a positive disparity represents that the object is perceived as diving into the screen. Unfortunately, the disparity still cannot faithfully reflect the perceptual stereoscopic strength. Generally, the built-in stereoscopic tool provides an auxiliary stereoscopic view of the editing scene to indicate the rough depth perception but it can only approximate stereoscopic strength and make slightly easier the job of achieving the stereoscopic requirement from the director. It remains a problem to guarantee the same stereoscopic strength for different screen sizes even with the same disparity.

Some past researches [18], [39] described geometric models of each step, considered different sources of distortion in each step, and focused on viewing conditions for personal head-tracking displays. Here, we notice that the audience generally watch stereoscopic contents in the upright posture and stare at the screen in a theater. Thus, we assume that the viewing angle is perpendicular to the screen and the viewing distance plays the major role in the viewing configuration. Generally, human perception is relative and stereo vision is no exception. In light of this, we propose a metric called geometric perceived depth percentage (GPDP), G, to represent the stereoscopic strength in term of the perceived depth, z, and the distance between the eyes and screen, Z_v. As shown in Figure 2, z is the relative depth from the perceived object point to the convergence plane and have a negative value when being in the front of the convergence plane. GPDP can be derived from the geometric relationship of $\frac{D(x,y)}{I_d} = \frac{z(x,y)}{Z_v + z(x,y)}$ [22] where I_d is the interocular distance as

$$\begin{aligned} \frac{D(x,y)}{I_d} &= \frac{\frac{z(x,y)}{Z_v}}{1+\frac{z(x,y)}{Z_v}} \\ \frac{I_d}{D(x,y)} &= \frac{-1}{G(x,y)} + 1 \; where \; G(x,y) = -\frac{z(x,y)}{Z_v} \\ G(x,y) &= \frac{D(x,y)}{D(x,y) - I_d} \end{aligned} \tag{3}$$



(a)

(b)

(c)

Fig. 4. The application of visual cues used in the proposed tool on a fighting scene of a castle and two warrior characters in the Maya editing window. (a) A snapshot of the editing scene along with a set of equally-spaced GPDP marker planes. (b) A snapshot of the editing scene shaded with our GPDP-based shading schemes of rainbow coloring. (c) A snapshot of the combination of both GPDP marker planes and shading schemes.

In film industry, it is often set as $63.5mm$, the average value for adults. The equation can be further rewritten as:

$$G(x,y) = \frac{\frac{F_l \times S_w}{F_w}\left(\frac{I_s}{Z_p} - \frac{I_s}{O}\right)}{\frac{F_l \times S_w}{F_w}\left(\frac{I_s}{Z_p} - \frac{I_s}{O}\right) - I_d}. \quad (4)$$

The proposed GPDP is intuitive and its interpretation is independent to the screen width. For example, when an object has its GPDP of 20%, it should be perceived as popping out of the screen with a distance equal to 20% of the distance from the eyes to the screen. When an object has its GPDP of -75%, it should be perceived as diving into the screen with a distance equal to 75% of the distance from the eyes to the screen. Compared to other metrics, the proposed GPDP offers the following benefits as an indication for predicting the degree of stereoscopic perception:

1) GPDP is more concise in depicting depth perception of the target audience. For example, when the central GPDP of an object is equal to 15%, this means that the object is located in front of the screen with a distance equal to 15% of the distance from the viewer to the screen.
2) GPDP linearly indicates the stereoscopic depth perception. For example, when an object with its central GPDP equal to 40%, its perceived depth in front of the screen is twice the perceived depth of an object with its GPDP equal to 20%.
3) GPDP takes the screen width into account and this is important for generating similar stereoscopic perception in different screening environments.
4) GPDP represents the distance ratio from the viewer to the screen, and thus, it can get rid of the issue of viewing distance variation.
5) GPDP is softly bounded in the range of $[0.5, -2.0]$ for comfortable viewing because the value of 0.5 represents the upper bound of the Panum Area [40] where single binocular vision is observed. Objects too close to our eyes may cause the difficulties of depth fusion.

IV. A Tool for Stereoscopic Parameter Setting

This section introduces some GPDP-based visual cues that help animators comprehend the depth perception of the scene. The key advantage of these visual cues is that they require neither rendering nor stereoscopic displays. The result is an intuitive tool that facilitates the stereoscopic parameter setting process.

A. Visualization and Manipulation Helper

Visualization is a graphical representation of data for either mental construct or auxiliary artefact for parameter manipulation. According to Tory and Moller's work [41], our tool aims at providing (1) a perceptual monitoring metric based on pre-attentive visual characteristics for evaluation of depth perception and (2) a manipulable medium for interactive exploration of different stereoscopic parameters in order to create a comfortable stereoscopic animation. In other words, our tool is designed to visually display the mental model and perceptual insight of depth perception for stereoscopic contents without any specific stereoscopic equipment. It should be intuitive and simple to understand and manipulate stereoscopy.

As an option for depicting the perceived depth, a set of uniformly separated GPDP marker planes can be added in the stereoscopic editing window as shown in Fig. 4(a). Animators are allowed to manipulate these planes for the desired depth effects. Although these marker planes are useful in indicating the stereoscopic effects created by different parameters, it is bothersome and nonintuitive to manipulate because animators must frequently switch between the rendering view from the active camera and the visualization view perpendicular to the active camera frustum for clearly checking the relative relationship among scene characters/objects and these planes. Furthermore,

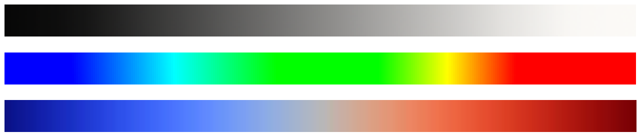


Fig. 5. The color schemes from the top to the bottom are gray-scale, rainbow, and cool-to-warm whose end colors are black and white, red and purple, and red and blue along with interpolation in the intensity, HSV, and MSH space.

when the number of objects/characters and depth complexity of the scene grows large, these planes become ineffective to indicate the depth information of all characters/objects. After discussing with animators, we decide to encode the GPDP of each object into its intensity or color to directly reflect depth perception. Thus, our system computes per-pixel GPDPs and transforms the computed GPDPs into colors according to a color map.

According to Eq. 3, GPDP is the ratio of the perceived depth to the viewing distance but perceived depth is not known during the setting process and it is not linearly related to the depth value inside the Panum area(i.e., the physical stereoscopic fusion region). GPDP takes this complex nonlinearity into consideration to provide more indication about the possible depth perception. GPDP denotes the relative position to the convergence plane which partitions stereo space from diving in to popping out. Diving and popping out create different illusions and effects. Thus, we choose to use a color scheme which defines the two end colors and transits from one end to the other. According to Moreland's study [42], the choice of the color scheme may affect the efficiency of information delivery. As shown in Fig. 5, the system has three different color schemes.

1) **Gray-scale color scheme**. The scheme chooses black and white colors to denote the small and large GPDPs respectively and interpolates the intensity between them according to GPDPs. It is simple and intuitive but easy to get confused with the flat shading in Maya's editor window. Note that the scheme is not perceptually linear as the human vision system is not linear to intensity.
2) **Rainbow color scheme**. The scheme chooses purple and red colors to denote the small and large GPDPs respectively and interpolates the Hue value in the HSV space. It is generally accepted and used in many visualization tools. Additionally, this scheme is intuitive to animators because the color temperature reflects the depth perception in the following manner: Red gives the sense of hazard and its hot temperature is similar to the threatening feeling given by the objects/characters popping out. Blue gives the sense of safeness and its low temperature matches the peaceful feeling when objects/characters are far away. It is however not perceptually linear due to the interpolation in the HSV space.
3) **Diversing cool-to-warm color scheme**. The scheme chooses diversing cool and warm colors to denote the small and large GPDPs respectively and interpolates in the MSH space [42] derived from the CIELAB space as shown at the bottom of Fig. 5. The CIELAB color space is designed to approximate the human vision [43] for a perceptually more linear scale, making it a proper color space for the color scheme of visualization. Similar to the rainbow color scheme, this scheme also has the advantage that the color temperature reflects the depth perception.

Fig. 4(b) shows an example of the GPDP-based shading using the rainbow color scheme. According to interviews with three animators, they generally prefer the rainbow color scheme because of their training background. However, from Fig. 8(c) and (d), we found that the cool-to-warm color scheme could distinguish stereoscopic layers better at times. Our system provides these color schemes as options to artists.

Our tool can combine both the color scheme and the marker planes for visualization as shown in Fig. 4(c). Fig. 6 gives an example usage flow of our tool. Once animators choose a screen width, per-pixel GPDPs are computed based on the depth of each pixel and stereoscopic parameters according to Equation 4. Animators can tune stereoscopic parameters to the desired stereoscopic effects by manipulating them and visualizing the resultant effects with the help of our tool.

One main advantage of using GPDP in the proposed system is that it provides a mean for maintaining the same depth perception when the screen width and viewing distance change. This is achieved by the following procedure for automatic parameter adjustment. When the animator decides to switch to another cinema screening setting, the screen width changes. Because the emphasized object/character is usually placed along the convergence plane, the animator may want to maintain this setting by keeping the convergence plane at its original location. In other words, Z_p keeps the same when changing to a new screen size. The only unknown left is I_s. As one option for determining it, the animator can select a representative point from the emphasized characters/objects as the reference and I_s can then be computed as

$$I_s = \frac{I_d F_w}{S_w F_l} \frac{Z_p O}{(O - Z_p)} \frac{G(x,y)}{(G(x,y)-1)}, \tag{5}$$

where O is the depth of the representative point chosen from the emphasized characters/objects. This option may however introduce a bias toward the reference character/object. A better option would be to use all GPDPs as constraints to find the best I_s and Z_p values so that the new GPDPs are close to the original ones by solving the following linear system:

$$\begin{bmatrix} 1 & \frac{-1}{Z(0,0)} \\ 1 & \frac{-1}{Z(0,1)} \\ \cdots & \\ 1 & \frac{-1}{Z(W,H)} \end{bmatrix} \begin{bmatrix} \frac{I_s}{Z_p} \\ I_s \end{bmatrix} = \begin{bmatrix} \frac{I_d F_w G(0,0)}{S_w F_l} \\ \frac{I_d F_w G(0,1)}{S_w F_l} \\ \cdots \\ \frac{I_d F_w G(W,H)}{S_w F_l} \end{bmatrix}, \tag{6}$$

where W and H are the width and height of the rendering target. I_s and Z_p can then be estimated by solving this linear system with SVD.

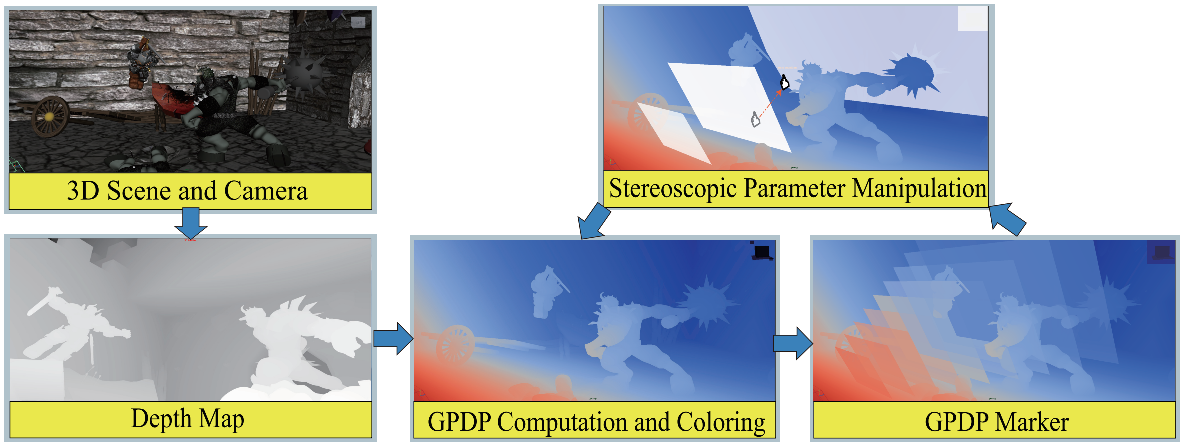
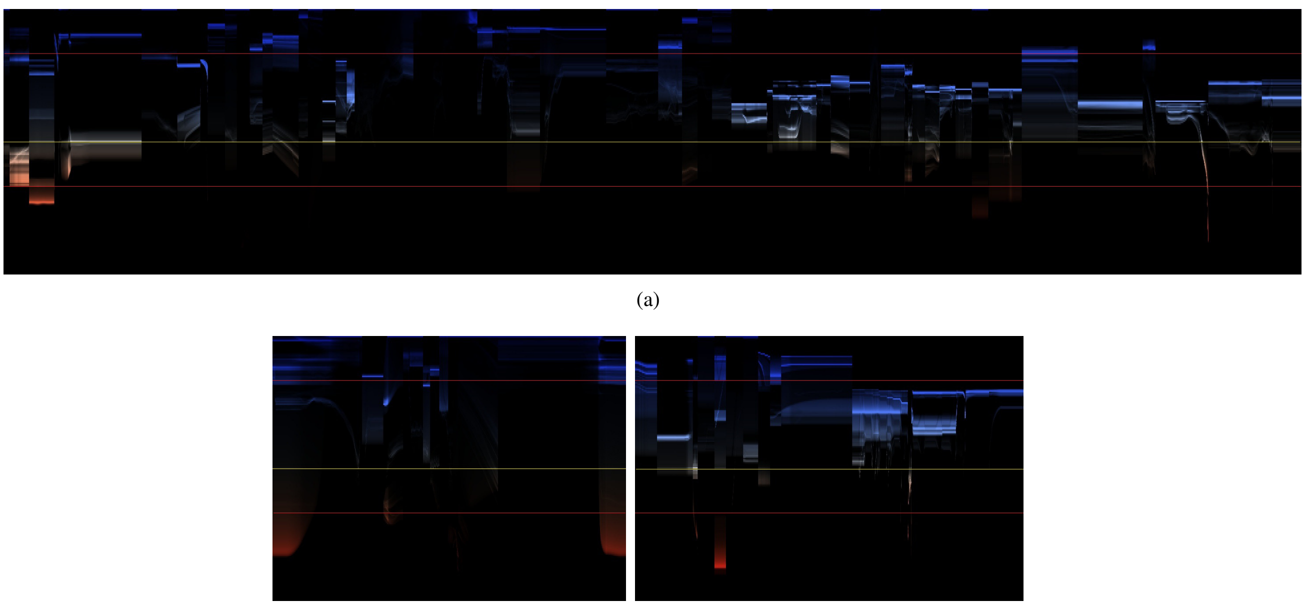


Fig. 6. An example flow of setting stereoscopic parameters using the proposed tool. First, the scene information is fed into the system and a depth map is computed based on the camera setting. Then, GPDPs of all pixels are computed based the depth values. They are used to shade pixels according to the chosen color scheme. Optionally, a set of uniformly separated GPDP marker planes can be placed to provide auxiliary indications to the depth volume and perception. Finally, the animator can edit the stereoscopic parameters with immediate visual feedback delivered by the GPDP-based shading scheme and the GPDP marker planes.



(a)

(b) (c)

Fig. 7. The GPDP histograms using the cool-to-warm color scheme for shots from three animations, Warrior (a), Gold Plunder (b) and Escape (c). The X-axis is for the frame index; the Y-axis shows GPDP values; and the intensity at each point indicates the accumulated number of pixels with a specific GPDP value. Additionally, the central white line marks where GPDP is equal to zero, and the top and bottom red lines mark where GPDP is equal to 33% and -66% respectively.

B. GPDP Histogram

Generally, a stereoscopic film should follow several empirical rules for comfortable stereoscopy:

1) **Comfortable zone**. Our brain can only fuse the left and right views for stereopsis inside Panum Area. However, our eyes prefer to have characters/objects perform near the convergence plane where our eyes converge two views to minimize extra muscular efforts for binocular fusion. As a result, animators generally let characters/objects perform within a comfortable zone inside Panum Area for comfortable stereoscopy such as those chosen in previous work [36], [44].
2) **Stereoscopic depth motion**. When depth motion velocity is too high, our eyes do not have enough fusion time to capture the transition and stereopsis is lost [34]. Therefore, the depth motion of a character/object should be small and smooth to maintain proper stereopsis and animators must pay attention to the stereoscopic transition velocity among shots.
3) **Stereoscopic budget ratio**. Our eyes use the ciliary muscles to fuse views for stereopsis. Objects with negative parallax, i.e., popping out of the screen, require much more efforts for stereoscopy [1]. Thus, our eyes get fatigue more easily when watching a video with more negative-parallax contents.

Therefore, artists generally control the ratio between negative- and positive- parallax contents for comfortable stereoscopy and only emphasize certain artistic points with negative parallax, letting eyes rest with very little efforts by using positive parallax for most parts [45].

The GPDP-based marker planes and shading scheme can help animators fulfill the first rule for each frame but they cannot be used to examine the temporal and accumulative relationship of frames within a shot for the other two rules. These rules can be better examined by observing GPDP distribution across temporal-GPDP domain within a shot. The distribution can be expressed graphically as a GPDP histogram in the following manner. For each frame, we partition the GPDP range of $[100\%, -100\%]$ uniformly into 101 bins and each bin collects the number of pixels whose GPDP values falling in the corresponding range. The GPDP distribution of a frame can be represented as a vertical color stripe in the histogram. By horizontally stacking distributions of all frames together, we obtain the GPGP histogram for a shot. The X-axis of the histogram represents the index of frames, and the Y-axis represents the GPDP values in a frame. The intensity represents the normalized count of pixels falling in each bin.

Fig. 7 shows examples of GPDP histograms for three animations, Warrior, Escape, and Gold Plunder. With the GPDP histogram, the stereoscopic rules can be checked as follows: First, if the GPDP value of a pixel in any frame is beyond the comfort zone marked as the red lines in Fig. 7, the shot violates the comfort zone rule. Second, the budget rule can be checked by examining whether the brightness below the X-axis is roughly equal to the brightness above the X-axis marked in Yellow. Finally, the depth motion can be estimated by computing the intensity gradients of the histogram between consecutive columns. If the gradients are too large, the velocity rule could have been violated.

V. Implementation

The proposed tool has been implemented into two popular animation tools in production: Maya and RenderMan. For Maya, two callbacks, 3dViewPreRender and 3dViewPostRender, are developed and registered into ModelPanel. When updating the viewport of a model panel, these callbacks are initiated to calculate per-pixel GPDPs and shade the scene according to the chosen GPDP color scheme for the depth perception of the view. For RenderMan, an imager shader is designed to shade the scene with computed per-pixel GPDPs through AOVs based on the camera information, screening information, and stereoscopic parameters passed from Maya. Other scene information such as geometrical primitives, lighting settings, and volume shaders passed into RenderMan is kept unchanged. Both implementations have negligible impacts in rendering time. We report all results on a workstation for artists, with dual 2.0GHz Intel Xeon 5130 processors, 4GB RAM, and NVIDIA Quadro FX 1500 graphics. The proposed solution has been used for the production of three academic feature animations as shown in Fig. 8. In general, the GPDP map can depict clearer and more correct depth perception than the depth map can.

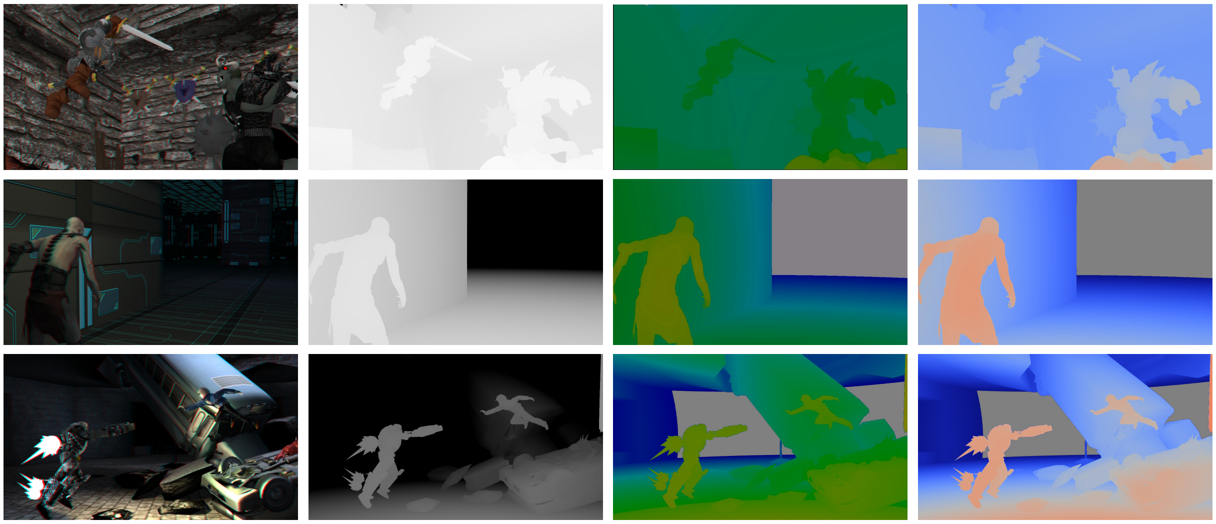
Animators of Digimax Inc. have adopted the proposed tool in production for accelerating their production of four commercial stereoscopic feature films: Quantun Quest and National Treasure I, II, and III. Fig. 9 shows a snapshot from National Treasure. We have collected comments about GPDP and the proposed tool from the animators. According to them, it is originally difficult to accommodate the perception differences among stereoscopic monitors, projectors, and IMAX screens with the built-in disparity-based stereoscopic auxiliary tool. GPDP acts as a stereoscopic ruler to relieve animators from the screen-width issue and shortens the gap between the stereoscopic producer and audience. Additionally, GPDP-based marker planes and shading also act as useful cues to clarify artistic instructions given by directors to animators for reduction of miscommunication between them. The tool helps them predict the possible perception without time-consuming rendering instead of guessing based on their experience. This makes the parameter setting process more efficient and saves quite a number of reviewing iterations. Supplementary materials can be found at the website http://graphics.csie.ntust.edu.tw/pub/GPDP/main.html.

VI. User Studies

In order to evaluate whether GPDP can correctly reflect the depth perception on different screen sizes and how useful the proposed tool is, two user studies were conducted. A S3D monitor, TV, and projector were used for studying stereoscopic effects in different viewing environments. The S3D monitor is Asus VG236H (1920×1080 pixels, 400 cd/m^2 brightness, 120 Hz refresh rate, 55 cm screen width) using NVidia 3D Vision and a pair of active shutter glasses; the S3D TV is Sharp LC-40W5T (1920×1080 pixels, 400 cd/m^2 brightness, 240 Hz refresh rate, 90 cm screen width) using Aquos Quattron 3D Vision and a pair of active shutter glasses; and the S3D projector is JVC DLA-X55R(1920×1080 pixels, 1200 lumen, 120 Hz refresh rate, 235 cm screen width) using JVC PK-EM2G 3D Vision and a pair of active shutter glasses. Before the study, participants were examined with the Nvidia stereoscopic 3D test to avoid obstruction of stereoscopic perception. The following sections reports details and results of these studies.

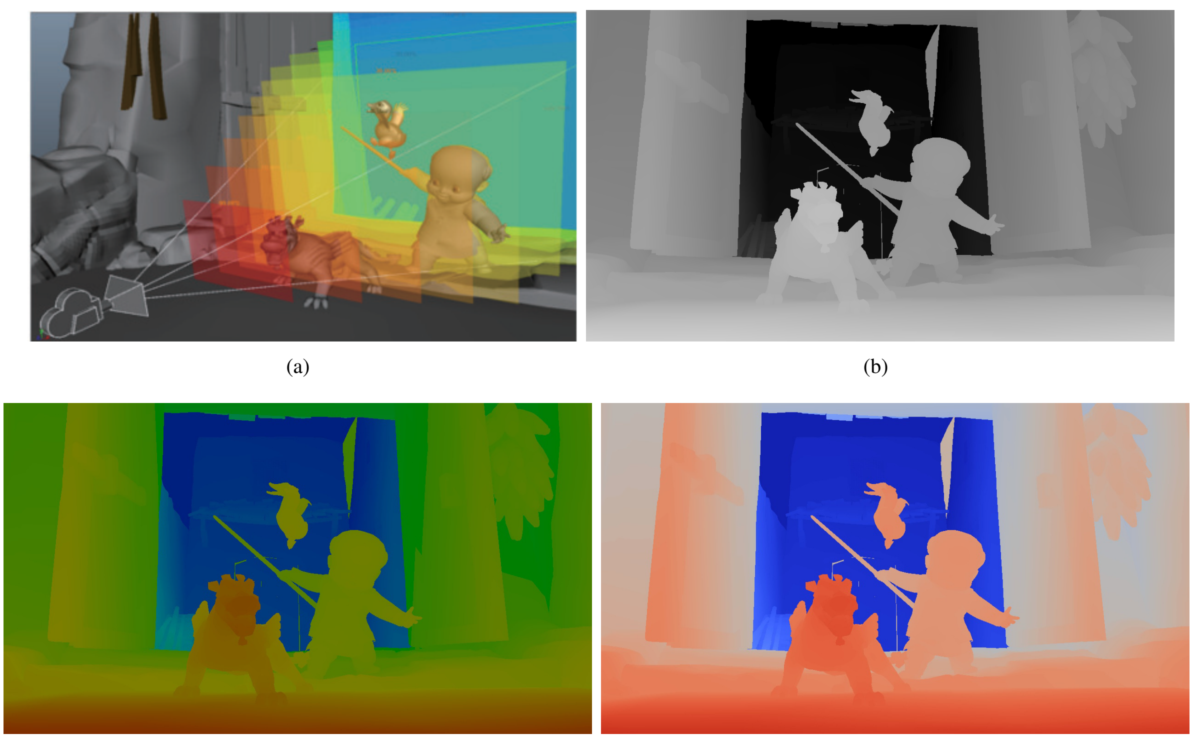
A. Effectiveness of GPDP across Different Screen Sizes

This study is intended to verify the effectiveness of GPDP across different screen sizes and all three devices were used with the physical setting shown in Fig. 10(a). For each participant, the order of the S3D devices is randomly decided to avoid a device-order bias. The participants sat in front of the S3D devices. Two scenes were used in this study: a simple scene and a complex one. Each scene has a main character whose central GPDP is 20%. The simple scene consists of only a plain sphere (Fig. 10(b)). In the



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

Fig. 8. Example uses of the system for three academic animations, Warrior (the 295-th frame), Escape (the 223-th frame), and Gold Plunder (the 900-th frame), from the top to the bottom. (a) The frame in the anaglyph form. (b) The depth map of the scene. (c) The GPDP-based shading result using the rainbow color scheme. (d) The GPDP-based shading result using the cool-to-warm color scheme.



(a) (b)

(c) (d)

Fig. 9. An example use of the system for a commercial animation, National Treasure. (a) A snapshot for the 110-th frame with the proposed tool in the Maya editing window. (b) Its depth map when viewing from the camera. (c) The GPDP-based shading result using the rainbow color scheme. (d) The GPDP-based shading result using the cool-to-warm color scheme.

Scene	Monitor		TV		Projector	
	Mean	Std	Mean	Std	Mean	Std
Simple	0.034	0.020	0.025	0.020	0.009	0.024
Complex	0.030	0.022	0.022	0.018	0.016	0.015

TABLE I
THE MEANS AND STANDARD DEVIATIONS OF GPDP ERRORS FOR THREE 3D DEVICES IN THE GPDP EFFECTIVENESS STUDY. THE GPDP OF THE MAIN CHARACTER IS 20% IN BOTH SIMPLE AND COMPLEX SCENES.

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
tm	2	0.0053	0.0026	11.517	3.8e-5
blk	42	0.018	0.00042	1.83	0.00891
Residual	84	0.019	0.00023		

TABLE II
THE RBD STATISTICS OF THE GPDP EFFECTIVENESS STUDY FOR THE SIMPLE SCENE

calculated using **R** [**?**]

complex scene, the main character fights with other characters in front of a complex background scene (Fig. 10(c)). This scene exhibits a more complex depth relationship. Because depth perception is influenced by many factors, the simple scene was designed to isolate other factors for studying the effectiveness of GPDP across different screen sizes. The complex scene was designed to illustrate that GPDP can still remain effective across different screen sizes despite the complex depth relationship and color structure of the scene. A physical depth marker was also presented on the floor along with the displays and its physical location was adjusted by the participant through commands to an administrator to point out the corresponding depth. After the participant felt that the marker is at the same depth as the object, the depth of the marker was recorded and its GPDP was calculated. For each device, the differences of the calculated GPDP values from the ground truth, 20%, were collected for all participants. Totally, for the simple scene, there were 49 subjects participated in our experiments with normal or corrected-to-normal vision, but only 43 passed the stereoscopic 3D test. Their ages range from 21 to 35 years; and 6 are females and 37 are males. For the complex scene, there were 46 subjects. Their ages range from 21 to 35 years; and 13 are females and 33 are males. The means and standard deviations of the perceived GPDP errors are listed in Table I. The mean errors for the simple scene are 3.4%, 2.5% and 0.9% in terms of GPDP for the monitor, the TV and the projector, respectively. And for the complex scene, the mean errors are 3.0%, 2.2% and 1.6%.

This study aims at evaluating whether the screen size is an important factor on the depth perception when using GPDP. The interfering factors, including sex, age, experience and others, are called nuisance variations. Differences among the subjects may make a significant contribution to the error variance and thereby affect the judgement. Therefore, a randomized block design (RBD) [46] is used to reduce error variances. RBD applies a blocking procedure to isolate nuisance variations to prevent estimation errors. The procedure forms n blocks of p homogeneous experimental units, where p is the number of investigated screen sizes and the n blocks correspond to the number of subjects in this study. The blocks should be formed with the following conditions:

1) $p \geq 2$ and $n \geq 2$.
2) n blocks should each contain p homogeneous units and the variability among units within a block should be less than the variability among units in different blocks.
3) p factors should be examined thoroughly in a random order within each block and therefore, RBD needs n sets of p homogeneous units.

As a result, the data was collected and listed in the format as shown in Fig. 11(a). The complete data set for this experiment is provided in the supplemental material. The procedure involves forming 43 blocks of 3 homogeneous experimental units. In Fig. 11(a), $Y_{i,j}$ is the score set as the difference between the measured GPDP and the designed GPDP. $Y_{i,j}$ is a composite that reflects the effects of factor j and block i plus all other sources of variations. The expectation for $Y_{i,j}$ from Kirk's book [46] can be expressed formally by a mixed model for type RB-p design as

$$Y_{ij} = \mu + \alpha_j + \pi_i + \varepsilon_{ij}$$

where μ denotes the overall population mean; α_j denotes the effect of the screen size for the j-th device; π_i denotes the effect of the i-th subject; and $\varepsilon_{i,j}$ denotes the experimental error. All these are unknown and thus, blocking approximates the estimation as

$$Y_{ij} - \overline{Y}_{..} = (\overline{Y}_{.j} - \overline{Y}_{..}) + (\overline{Y}_{i.} - \overline{Y}_{..}) + (Y_{ij} - \overline{Y}_{.j} - \overline{Y}_{i.} + \overline{Y}_{..})$$

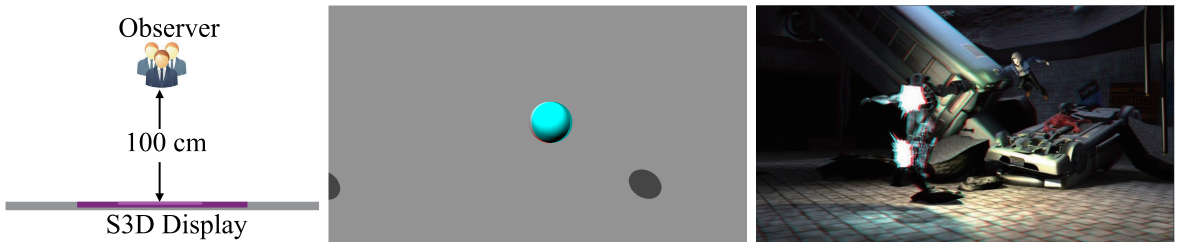
The overall deviation can be expressed as

$$\begin{aligned} \sum_{j=1}^{p}\sum_{i=1}^{n}(Y_{ij} - \overline{Y}_{..})^2 &= n\sum_{j=1}^{p}(\overline{Y}_{.j} - \overline{Y}_{..})^2 + p\sum_{i=1}^{n}(\overline{Y}_{i.} - \overline{Y}_{..})^2 \\ &+ \sum_{j=1}^{p}\sum_{i=1}^{n}(Y_{ij} - \overline{Y}_{.j} - \overline{Y}_{i.} + \overline{Y}_{..})^2 \end{aligned}$$

Then, these parameters can be used to compute the F value of the collected data on the screen-sized factor according to Table 6.2-2 of the book [46]. After computing F-variance, Table II lists the result of ANOVA, which tests whether the differences among subjects are important and whether the mean perceptual depth errors for 3 devices are all equal at the 0.01 level of significance for both scenes. The result shows that the screen size of a 3D device is not a factor for depth perception when using GPDP for depth manipulation and the differences among subjects do not affect the perception errors. Generally, subjects agreed that the stereoscopic perception in all three devices are roughly the same for both simple and complex scenes.

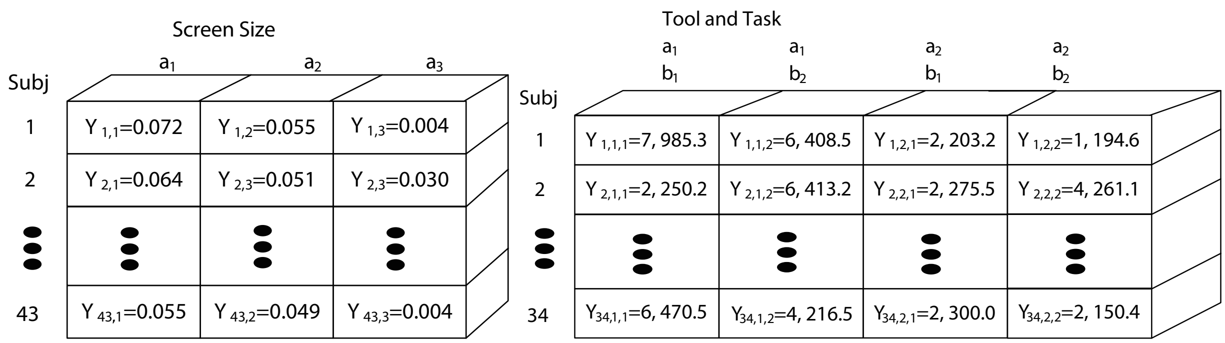
B. *Usefulness of the Proposed Tool*

This study is intended to verify the usefulness of our proposed tool and the S3D TV was used with the physical setting shown in Fig. 12(a). Subjects were asked to



(a) (b) (c)

Fig. 10. Experiment setting of the GPDP effectiveness study. (a) The subject sits in front of a S3D device with a distance of $100cm$ to the screen. A stereoscopic image of the scene in (b) or (c) is displayed and participants are asked to locate the perceived depth. (b) The simple scene consists of a sphere located at $G = 20\%$. (c) The complex scene has a main character located at $G = 20\%$, an enemy character and a complex background. For display purpose, we show the red-cyan anaglyph format in the paper. In the experiment, the binocular format was used.



(a) (b)

Fig. 11. (a) The data arrangement for type RB-3 of the randomized block design (RBD). Y_{ij} denotes a score in one of the $i = 1, \cdots, n$ blocks for subjects and $j = 1, \cdots, p$ factors for screen sizes. The j-th factor mean is computed as $\overline{Y}_{.j} = \sum_{i=1}^{n} Y_{ij}/n$, the i-th block mean is computed as $\overline{Y}_{i.} = \sum_{j=1}^{p} Y_{ij}/p$, and the grand mean is computed as $\overline{Y}_{..} = \sum_{i=1}^{n}\sum_{p=1}^{p} Y_{ij}/np$. (b) The data arrangement for RBF-22 of the randomized block factorial design (RBFD). Y_{ijk} denotes a score in one of the $i = 1, \cdots, n$ blocks for subjects, $j = 1, \cdots, p$ for tool types, and $j = 1, \cdots, q$ for scenes. Since there are two tools, the Maya built-in and our proposed tool, and two scenes, there are totally four combinations for each subject.

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
tm	2	0.0048	0.0024	8.093	5.8e-4
blk	45	0.018	0.00040	1.37	0.10391
Residual	94	0.027	0.00030		

TABLE III
THE RBD STATISTICS OF THE GPDP EFFECTIVENESS STUDY FOR THE COMPLEX SCENE CALCULATED USING **R** [47].

	# of Ops		Time(sec)	
	Mean	Std	Mean	Std
task 1(Maya)	5.17	1.29	479	166
task 1(Ours)	1.35	0.60	247	104
task 2(Maya)	4.44	1.18	435	182
task 2(Ours)	2.44	1.00	254	99

TABLE IV
THE MEANS AND STANDARD DEVIATIONS OF THE NUMBER OF OPERATIONS AND THE TIME TO OBTAIN THE PROPER STEREOSCOPIC SETTING FOR TASK 1 AND 2 IN THE USEFULNESS STUDY OF THE PROPOSED TOOL.

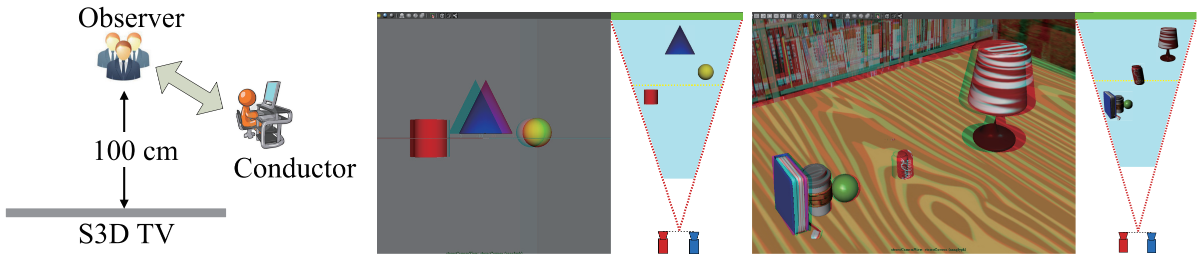
	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
tm1	1	288.26	288.26	261.571	2e-16
tm2	1	1.06	1.06	0.961	0.329
tm1*tm2	1	28.26	28.26	25.647	1.35e-6
Residual	132	145.47	1.10		

TABLE V
THE RBFD STATISTICS FOR THE NUMBER OF OPERATIONS OF THE USEFULNESS STUDY OF THE PROPOSED TOOL CALCULATED BY**R** [47].

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
tm1	1	1447855	1447855	70.840	5.61e-14
tm2	1	11744	11744	0.575	0.450
tm1*tm2	1	22195	22195	1.086	0.299
Residual	132	2697882	20439		

TABLE VI
THE RBFD STATISTICS FOR THE OPERATION TIME OF THE USEFULNESS STUDY OF THE PROPOSED TOOL CALCULATED BY **R** [47] USING THE DATA COLLECTED FROM 34 VALID SUBJECTS.

set stereoscopic parameters for two scenes as shown in Fig. 12(b) and (c). The first scene consists of a simple diffuse cylinder, cube, sphere, and cone in the front and two diffuse walls in the back. Subjects were asked to have the cylinder pop out of the screen with a distance of 10 to 15 % of the distance from the eye to the screen, the cube center at the convergence plane, the sphere and cone dive into the back of the screen with a distance of 5 to 10 % and 25 to 30 % respectively. The second scene consists of a textured cup, coke can, ball, and lamp in the front and a textured book shelf, floor, and stone wall in the back. Subjects were asked to have the coke can dive into the



(a) (b) (c)

Fig. 12. (a) The subject sat next to a computer for operating Maya and with a distance of 100*cm* to the S3D TV. He/she was asked to set the stereoscopic parameters using the Maya built-in tool and our tool. The scene was rendered with the parameters and displayed on the TV. An instructor sat next to the subject and gave instructions according to the rendered frame. (b) and (c) shows the scenes used for studying the usefulness of the proposed tool. For each scene, the right shows the desired arrangement of objects inside the view volume from a top-down view. The left shows a snapshot in the anaglyph format taken from the Maya editing window when using the Maya built-in tool for parameter setting. (b) A simple scene consists of simple diffuse objects with different colors and depth values. Two diffuse walls are placed at the back. (c) A more complex scene consists of objects with textures and different depth values. Two textured walls are placed at the back.

screen but next to the convergence plane, the ball, cup, and book pop out of the screen with a distance of 5 to 10 % of the distance from the eye to the screen, and the lamp dive into the screen with a distance of 5 to 10 %. These two scenes were designed in a similar way with the scenes used for training beginners based on an interview with an experienced stereoscopic animator.

Two tools were used to complete the tasks of setting stereoscopic parameters for these two scenes. One is the auxiliary anaglyph 3D previewing tool provided by Maya and the other is the proposed tool. Although Maya provides another built-in option using Nvidia Quadro with active shutter glasses but both mechanics provide the stereoscopic view of the scene and thus, for easiness, we choose anaglyph one. The Maya built-in tool is a disparity-based auxiliary tool as it directly shows disparity-based rendering results on the screen. Furthermore, because of the nonlinear depth transformation of parallax and disparity, it is not intuitive to provide reasonable indication using similar shading concepts developed in the paper. And, to our best knowledge, there is no auxiliary tool built based on these two metrics publicly available. The built-in tool of Maya is operated as follows: (1) Subjects are asked to add the stereoscopic camera into the scene. (2) Subjects are instructed to use the default interaxial separation and zero parallax for the initial result and activate the anaglyph 3D previewing tool. (3) Subjects adjust the interaxial separation and zero parallax until they are satisfied with the stereoscopic preview when watching with the anaglyph 3D glasses. (4) The result is rendered to show on the S3D TV. The instructor reviews it and gives out instructions to help subjects to adjust the parameters. (5) Repeat 3 and 4 until reaching the stopping criteria. Our auxiliary tool is operated in the following manner: (1) Subjects are asked to add the stereoscopic camera into the scene. (2) Subjects are instructed to use the default interaxial separation and zero parallax for the initial result and activate the proposed tool. (3) Subjects are also instructed to input the width of the screen in the unit of *cm*. (4) Subjects adjusts the interaxial separation and zero parallax until he/she is satisfied with the stereoscopic result with the help of the proposed tool. (5) The result is rendered to show on the S3D TV. The conductor reviews it and gives out instructions to help subjects to adjust the parameters. (6) Repeat 4 and 5 until reaching the stopping criteria. There are two stopping criteria: the number of trials exceed 10 times or the requirement is satisfied. To avoid the studying effect, the order of using these two tools was randomly chosen for each subject. During the study, the following information was recorded: (1) how many operations it took the subject to reach the desired stereoscopic effects; (2) how much time (only including operation but not rendering and evaluation) the subject spent for obtaining the desired stereoscopic effects. In total, 34 subjects participated in our experiments, and all are with normal or corrected-to-normal vision and have no difficulty in stereoscopic fusion. Their ages range from 21 to 35 years; 19 are females and 15 are males. In addition, all of them have at least two years of experiences using Maya and are familiar with the tools provided by Maya but none of them has experience in stereoscopic parameter setting. The mean and standard deviation of the number of operations and time for Task 1 and 2 are listed in Table IV. With the proposed tool, both the number of operations and the time to the proper setting were roughly reduced to 50% compared to Maya's built-in tool.

We use a similar statistic analysis as the previous study. The main difference is that there are two different tasks in this study and it is an extra factor. Those nuisance variations can be avoided by using the randomized block factorization design (RBFD). The data was collected and listed in the format as shown in Fig. 11(b) and the complete data of this study is provided in the supplemental material. The procedure involves 34 blocks of 2×2 homogeneous experimental units, where 34 blocks correspond to the subjects and 2×2 units correspond to 2 tools and 2 tasks respectively. In Fig. 11(b), $Y_{i,j,k}$ is the score set for the number of operations and time required to finish the task. According to Kirk's book [46], the expectation for $Y_{i,j,k}$ can be expressed formally by a mixed model for type RBF-pq design as

$$Y_{ij} = \mu + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \pi_i + \varepsilon_{ijk}$$

where μ denotes the overall population mean; α_j denotes the effect of the j-th tool; β_k denotes the effect of the k-th task; $(\alpha\beta)_{j,k}$ denotes the joint effect of the j-th tool and the k-th task; π_i denotes the effect of the i-th subject; and $\varepsilon_{i,j,k}$ denotes the experimental error. The single and overall deviation can be derived from experimental data in a similar manner as presented in Section VI-A. Finally, the F value of the collected data on the tool types is computed according to Table 9.5-1 of the book [46]. After computing F-variance, Table V and VI report the results of ANOVA which tests whether the differences among subjects are important and whether our tool enhances the efficiency of stereoscopic parameter setting at 0.001 level of significance. The result shows that the tool type is an affecting factor for the parameter setting efficiency. In other words, the proposed tool does improve the efficiency of the stereoscopic parameter setting process.

VII. Conclusion

Because GPDP takes the screen width and the viewing distance into account, it is a more intuitive and universal metric for depth perception compared to commonly used parallax and disparity. Taking one step further, we use GPDP to design shading schemes to connect depth perception with psychovisual coloring in order to build the coherence between physics and psychological emotion. The GPDP-based shading method helps visualize the stereoscopic depth perception without the need of any special 3D equipment and facilitates the communication between producers and artists. Furthermore, the shading scheme can further be incorporated with a stereoscopic comfort volume and GPDP marker planes to help animators set up the stereoscopic keys. The effectiveness of GPDP and the usefulness of the proposed tool have been verified by a couple of user studies.

Our system has limitations and there are a few future research directions. First, GPDP is derived from geometric aspects without considering any psychophysical factor. In order to give animators more indications about possible depth perception, we would like to quantize the effects of the perceived depth and its relative temporal and spatial variation to its neighborhood in a pixel-based or patch-based manner using psychophysiological analysis similar to [48], [**?**] Second, the GPDP-based shading scheme can help animators and producers predict the possible depth perception but it is still a metaphor and requires mental transformation. We would like to explore other visualization schemes for more intuitive depth perception.

References

[1] B. Mendiburu, *3D Movie Making Stereoscopic Digital Cinema from Script to Screen*. Focal Press, 2010.

[2] G. Sun and N. S. Holliman, “Evaluating methods for controlling depth perception in stereoscopic cinematography,” in *Proc. SPIE, Stereoscopic Displays and Applications XX*, vol. 7237, 2009.

[3] P. Didyk, T. Ritschel, E. Eisemann, K. Myszkowski, and H.-P. Seidel, “A perceptual model for disparity,” *ACM Trans. Graph.*, vol. 30, no. 4, pp. 96:1–96:10, Jul. 2011.

[4] P. Didyk, T. Ritschel, E. Eisemann, K. Myszkowski, H.-P. Seidel, and W. Matusik, “A luminance-contrast-aware disparity model and applications,” *ACM Transactions on Graphics (Proceedings SIGGRAPH Asia 2012, Singapour)*, vol. 31, no. 6, 2012.

[5] S.-P. Du, B. Masia, S.-M. Hu, and D. Gutierrez, “A metric of visual comfort for stereoscopic motion,” *ACM Trans. Graph.*, vol. 32, no. 6, pp. 222:1–222:9, 2013.

[6] G. Sharp, “RealD discusses stereo contrast ratio (SCR),” 2013. [Online]. Available: http://tinyurl.com/n7qn9xq

[7] G.-M. Su, Y.-C. Lai, A. Kwasinski, and H. Wang, *3D Visual Communications*. John Wiley and Sons, 2012.

[8] S. Reichelt, R. Hussler, G. Flitterer, and N. Leister, “Depth cues in human visual perception and their realization in 3d displays,” *Three-Dimensional Imaging, Visualization, and Display*, pp. 76 900B–76 900B–12, 2010.

[9] J. E. Cutting and P. M. Vishton, “Perceiving layout and knowing distance: the integration, relative potency and contextual use of different information about depth,” *Perception of Space and Motion*, pp. 69–118, 1995.

[10] O. Ostberg, “Accommodation and visual fatigue in display work,” *Displays*, vol. 2, no. 2, pp. 81–85, 1980.

[11] A. J. Woods, T. Docherty, and R. Koch, “Image distortions in stereoscopic video systems,” in *Proc. SPIE, Stereoscopic Displays and Applications IV*, vol. 1915, 1993, pp. 36–48.

[12] V. S. Grinberg, G. Podnar, and M. W. Siegel, “Geometry of binocular imaging,” in *Proc. of the IS&T/SPIE Symp. on Electronic Imaging, Stereoscopic Displays and applications, Vol.2177*, 1994, pp. 56–65.

[13] S. Palmer, *Vision Science: Photons to Phenomenology*. The MIT Press, 2002.

[14] P. Howard and B. Rogers, *Seeing in Depth*. Oxford Univresity Press, 2002.

[15] F. L. Kooi and A. Toet, “Visual comfort of binocular and 3D displays,” *Displays*, vol. 25, no. 2, pp. 99–108, 2004.

[16] S. Yano, M. Emoto, and T. Mitsuhashi, “Two factors in visual fatigue caused by stereoscopic HDTV images,” *Displays*, vol. 25, no. 4, pp. 141–150, 2004.

[17] B. Julesz, *Foundations of Cyclopean Perception*. The MIT Press, 2006.

[18] R. T. Held and M. S. Banks, “Misperceptions in stereoscopic displays: A vision science perspective,” in *Proceedings of the 5th Symposium on Applied Perception in Graphics and Visualization*, ser. APGV ’08, 2008, pp. 23–32.

[19] D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks, “Vergencevaccommodation conflicts hinder visual performance and cause visual fatigue,” *Journal of Vision*, vol. 8, no. 3, pp. 1–30, 2008.

[20] M. Lambooij, W. IJsselsteijn, and M. Fortuin, “Visual discomfort and visual fatigue of stereoscopic displays: A review,” *Journal of Imaging Technology and Science*, vol. 53, pp. 1–14, 2009.

[21] T. Shibata, J. Kim, D. M. Hoffman, and M. S. Banks, “The zone of comfort: Predicting visual discomfort with stereo displays,” *Journal of Vision*, vol. 11, no. 6, 2011.

[22] F. Zilly, J. Kluger, and P. Kauff, “Production rules for stereo acquisition,” *Proceedings of the IEEE*, vol. 99, no. 4, pp. 590–606, 2011.

[23] Y. Ju Jung, S.-i. Lee, H. Sohn, H. Wook Park, and Y. Man Ro, “Visual comfort assessment metric based on salient object motion information in stereoscopic video,” *Journal of Electronic Imaging*, vol. 21, no. 1, pp. 011 008–1–011 008–16, 2012.

[24] B. Pollock, M. Burton, J. W. Kelly, S. Gilbert, and E. Winer, “The right view from the wrong location: Depth perception in stereoscopic multi-user virtual environments,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, no. 4, pp. 581–588, 2012.

[25] K. Templin, P. Didyk, T. Ritschel, K. Myszkowski, and H.-P. Seidel, “Highlight microdisparity for improved gloss depiction,” *ACM Trans. Graph.*, vol. 31, no. 4, pp. 92:1–92:5, 2012.

[26] W. J. Tam, F. Speranza, S. Yano, K. Shimono, and H. Ono, “Stereoscopic 3d-tv: Visual comfort,” *Broadcasting, IEEE Transactions on*, vol. 57, no. 2, pp. 335–346, June 2011.

[27] E. W. JIN, M. E. MILLER, S. ENDRIKHOVSKI, and C. D. CEROSALETTI, “Creating a comfortable stereoscopic viewing experience: effects of viewing distance and ?eld of view on fusional range.” in *Proc. SPIE 5664*, 2006, pp. 10–21.

[28] E. W. Jin, M. E. Miller, and M. R. Bolin, “Tolerance of misalignment in stereoscopic systems,” in *Proc. ICIS*, 2006, pp. 370–373.

[29] J. Li, M. Barkowsky, and P. Le Callet, “Study on visual discomfort induced by stimulus movement at fixed depth on stereoscopic

displays using shutter glasses," in *In Third InternationalWorkshop on Quality of Multimedia Experience (QoMEX)*, 2011, pp. 1–8.

[30] J. Li, M. Barkowsky, and P. Callet, "The influence of relative disparity and planar motion velocity on visual discomfort of stereoscopic videos," in *In Third InternationalWorkshop on Quality of Multimedia Experience (QoMEX)*, 2011, pp. 155–160.

[31] S.-H. CHO and H.-B. KANG, "Subjective evaluation of visual discomfort caused from stereoscopic 3d video using perceptual importance map." in *In TENCON 2012 - 2012 IEEE Region 10 Conference,*, 2012, pp. 1–6.

[32] X. Yang, L. Zhang, T.-T. Wong, and P.-A. Heng, "Binocular tone mapping," *ACM Trans. Graph.*, vol. 31, no. 4, pp. 93:1–93:10, Jul. 2012.

[33] K. Masaoka, A. Hanazato, M. Emoto, H. Yamanoue, Y. Nojiri, and F. Okano, "Spatial distortion prediction system for stereoscopic images," *Journal of Electronic Imaging*, vol. 15, no. 1, pp. 013 002–013 002–12, 2006.

[34] J. Kim, D. Kane, and M. S. Banks, "Visual discomfort and the temporal properties of the vergence-accommodation conflicts," *SPIE. Stereoscopic Displays and Virtual Reality Systems*, vol. 8288, pp. 1–11, 2012.

[35] H. Pan, C. Yuan, and S. Daly, "3D video disparity scaling for preference and prevention of discomfort," in *SPIE. Stereoscopic Displays and Applications XXII*, vol. 7863, 2011, pp. 786 306–1.

[36] M. Lang, A. Hornung, O. Wang, S. Poulakos, A. Smolic, and M. Gross, "Nonlinear disparity mapping for stereoscopic 3D," *ACM Trans. Graph.*, vol. 29, no. 3, p. 10, 2010.

[37] A. Smolic, P. Kauff, S. Knorr, A. Hornung, M. Kunter, M. Muller, and M. Lang, "Three-dimensional video postproduction and processing," *Proceedings of the IEEE*, vol. 99, no. 4, pp. 607–625, 2011.

[38] N. A. Dodgson, "Variation and extrema of human interpupillary distance, in stereoscopic displays and virtual reality systems," in *Proc. SPIE 5291*, 2004, pp. 36–46.

[39] Z. Wartell, L. F. Hodges, and W. Ribarsky, "A geometric comparison of algorithms for fusion control in stereoscopic htds," *IEEE Transactions on Visualization and Computer Graphics*, vol. 8, no. 2, pp. 129–143, 2002.

[40] G. K. von Noorden and E. C. Campo, *Binocular Vision and Ocular Motility Theory and Management of Strabismus*, 6th ed. Mosby, 2001.

[41] M. Tory and T. Moller, "Human factors in visualization research," *Visualization and Computer Graphics, IEEE Transactions on*, vol. 10, no. 1, pp. 72–84, 2004.

[42] K. Moreland, "Diverging color maps for scientific visualization," in *Proceedings of the 5th International Symposium on Advances in Visual Computing: Part II*, ser. ISVC '09, 2009, pp. 92–103.

[43] Wikipedia, "Lab color space." [Online]. Available: https://en.wikipedia.org/wiki/Lab_color_space

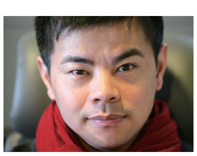
[44] T. Oskam, A. Hornung, H. Bowles, K. Mitchell, and M. Gross, "OSCAM - Optimized stereoscopic camera control for interactive 3D," *ACM Trans. on Graphics (Proc. SIGGRAPH)*, vol. 30, no. 6, pp. 189:1–189:8, 2011.

[45] C. Dsouza, *Think in 3D: Food For Thought for Directors, Cinematographers and Stereographers*. Clyde DeSouza, 2012.

[46] R. Kirk, *Experimental Design*, 2nd ed. Brooks/Cole Publishing Company, 1982.

[47] "The R project for statistical computing," 2013. [Online]. Available: http://www.r-project.org/

[48] J. A. Ferwerda, S. N. Pattanaik, P. Shirley, and D. P. Greenberg, "A model of visual adaptation for realistic image synthesis," in *SIGGRAPH '96*, 1996, pp. 249–258.



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