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3D Distortion Modeling: A software package to represent image space perception in stereoscopic displays

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Abstract

This paper describes a software package called 3D Distortion Model (3DDM), which we developed to provide a better understanding of stereoscopic display design. The software is based on contemporary geometric models of stereoscopic perception from the scientific literature. The user can input stereoscopic display design parameters, and the software will calculate the resultant image metrics and perceptual space distortions. There are several options for visualization of these results. In a live mode option, subsequent changes to design parameters will update calculations and imagery in real time. Additionally, the user can lock specific parameter values and explore how changes in one input variable will necessitate changes in another. Using both numerical output and provided figures, the user can predict how specific parameter changes and subsequent perceptual distortions may impact the usability of the display itself. This software provides the capability for considering scene information, display design and the human user experience.

Background

High fidelity stereoscopic displays can be vital to military, robotics, and medical applications. Creators of such systems must consider the perceptual effects of the many design choices, which can be challenging. The three-dimensional distortion modeling (3DDM) software described in this paper was developed to provide precise estimates of the perceptual consequences of stereoscopic display design choices. A graphical user interface (GUI) is presented upon running the executable, prompting the user to select from one of three geometric models: Woods et al. (1993) [1]; Held and Banks (2008) [2]; or Gao et al. (2018) [3]. Selecting one of these three options loads a separate and unique GUI that allows the user to input the display and viewing parameters relevant to that model. Modifiable parameters include those related to the scene cameras (e.g., camera separation), the display (e.g., screen width), and the viewer (e.g., head and eye position). The software then estimates the distortion that changes in these parameters introduce in the perceptual image space the user experiences. The calculated distortion metrics include convergence distance, display field of view, vergence-accommodation mismatch, hyperstereo, and others. There are several summary figures generated from the models, all of which represent the transformation from object to image space. This software provides the vision research community with a precise simulation of perceptual space when considering parameters of stereoscopic displays. For example, the 3DDM software was used to compute 3D distortions in our previous research [4].

Methods

The 3DDM software is an executable that uses MATLAB Runtime 9.14, which is a free download from The Mathworks (Natick, MA). The executable opens the application window, as shown in Figure 1. Upon launch, the user must first click "Select 3DDM System Folder", which opens a file browser window. The folder selected by the user should contain the configuration files, aircraft outline files, and unit conversion tables provided with the tool. Once selected, the individual model functions are available to select. Note that multiple model applications can be opened concurrently.

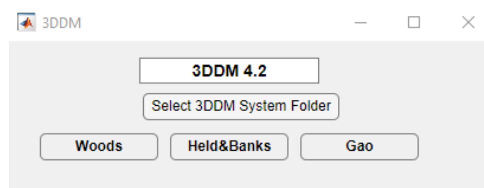

Figure 1. *GUI that appears after first opening 3DDM executable.*

Each model application is comprised of a main graphical user interface (GUI) with object space input and image space output parameters, an "additional parameter" GUI for more complex input options, and a GUI for plotting image space distortions. Upon opening any of the model functions, all values are zero and units are undefined in the main GUI. The user must press the button labeled 'Open Digital I/O' in the Program Control section, select 'Restore Configuration', and choose the .xlsx file they want to load. This is a necessary step to start using each model. Upon loading the file, the values and units will autofill, and the user will be able to interact with the GUI. Included with the software is an example .xlsx file for each model application.

Woods et al. Model

The main Woods et al. model GUI is pictured in Figure 2. An example RVS set-up is shown already loaded. This example will be used in all models in this paper and shown in the resultant image spaces. The Woods et al. Parameters panel (top left) provides direct access to the parameters found in [1], with corresponding nomenclature. Values may be typed in or adjusted with the slider bars. Units and upper/lower slider limits may be adjusted in the .xlsx parameter file. The calculated parameter checkboxes in the convergence group allow the user to select which parameter automatically updates when one of the other three is manually changed, as necessitated by the model. The Woods et al. Info panel (top right) presents the values of the output variables from this model. All values aside from compression and "fofix" are calculated automatically. Note that "fofix", or focus-fixation mismatch, is the nomenclature used here to describe vergence-accommodation mismatch. Compression and fofix are calculated once the user specifies the object space z-axis coordinates and hits enter or pressed the 'Run' button (Program Control panel). The lock checkboxes are

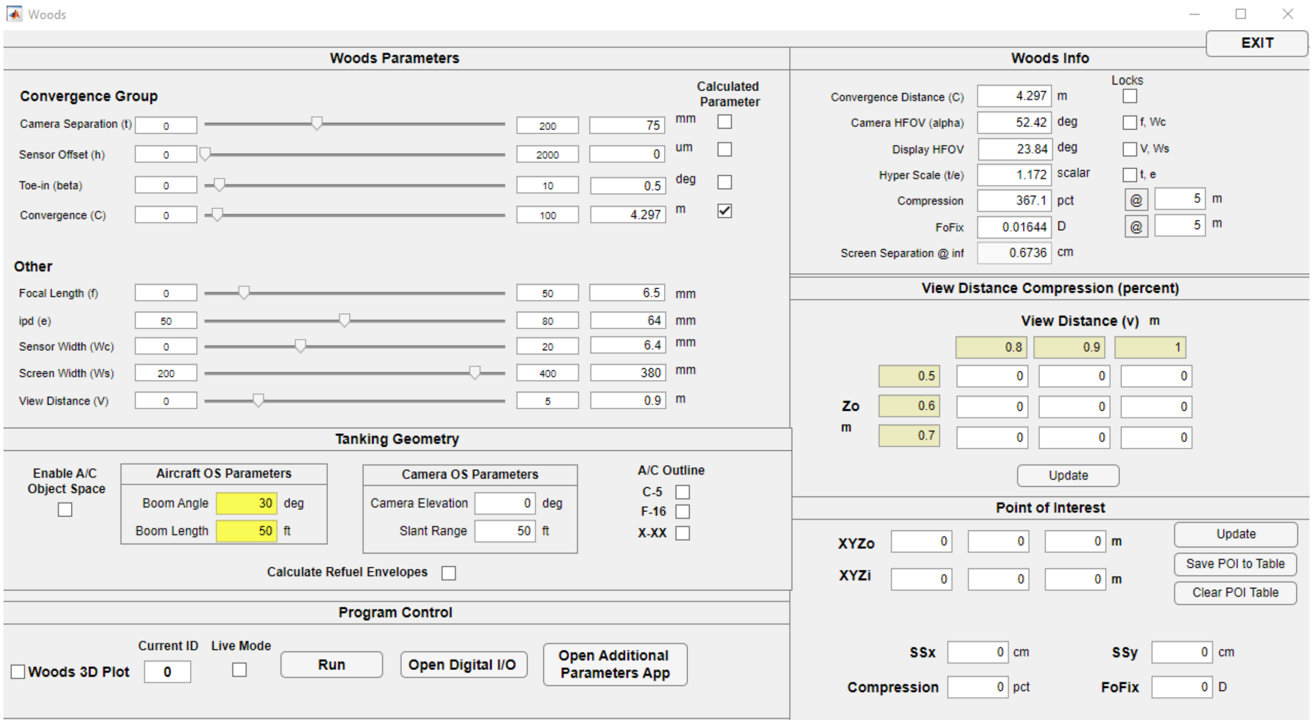

Figure 2. *Main Woods et al. Model GUI*

provided to constrain certain parametric relationships in order to "lock" the info panel variables. This allows the user to investigate how one input value must compensate when changing another (e.g. locking camera field-of-view, then increasing focal length to see how sensor width must change).

The View Distance Compression Panel (middle right) provides additional percent compression data as a two-dimensional function of both the z-axis value in object space (x and y set to zero) and the viewing distance of the display. The Update button will update the data table with changes to the input variables. The Point of Interest (POI) panel (bottom right) supports a query in object space which displays the corresponding image space coordinates, screen separation components, compression, and fofix. 'Save POI To table' will save the current entry to a temporary file. You can do this with multiple entries in a row by pressing save after each one. 'Clear POI Table' will erase the temporary file. To permanently save the temporary POI table, the user must press the 'Open Digital I/O' button and select 'Save POI Table'.

Two coordinate system options are supported in the Woods et al. model GUI, Camera Object Space (OS) and Aircraft Object Space (OS). The Camera OS configuration is analogous to [1]. The Aircraft OS configuration offers additional features to support a specific applied use case of a stereoscopic display: aerial refueling operations. Specifically in the Tanking Geometry panel (middle left), parameters of the refueling boom design (angle and length) and scene camera elevation/slant are configurable. There are also checkboxes to enable receiver aircraft outlines when running the image space plot.

The Program control panel is available in all three model GUIs. The Run button updates calculations based on the current data set. The Open Digital I/O Button opens the Digital Input/Output window which allows the user to restore a saved configuration, save the current configuration, save the GUI window as an image file, and of course, save the POI table. The user can also save a diagnostic file, which shows step-by-step calculations in an .xlsx file. The Open Additional Parameters Button opens a window with the same name, which has three separate tabs. One is the 6DOF Parameters Tab, which allows the user to set the image space figure parameters and has additional head and camera options (e.g. roll). The Auxiliary Tab allows the user to set separate left/right eye and left/right camera parameters and has additional aircraft object space options. The Gao et al. Graphics Tab will be described in the Gao et al. model section of this paper. The Woods et al. 3D Plot checkbox opens a Woods et al. graphics window: the user must check the checkbox and then click the 'Run' button. The Current ID window shows the ID of the currently active graphics window. To update the graphics when the input parameters are modified in the main GUI, the user must select the live mode checkbox.

Held and Banks Model GUI

The main Held and Banks model GUI is shown in Figure 3. Similar to the Woods et al. model GUI, input parameter variables are grouped on the left side of the screen. There are more variables available in this model, though many of them are in the auxiliary tab if needed in Woods et al. mode. The variables are grouped so that a calculated parameter must be checked, as changing one variable will necessitate a change of one of the others in the group. Locks are still available under the info variable grouping. Image space object slant calculation variables are unique to this model, which are calculated based on estimates from the human visual system with an 80/20 weighting of horizontal disparity and eye position-bases estimation to horizontal and vertical disparity-based estimation. These percent values can be changed by the user. The slant estimates are also based on the cube parameters, as defined in the Object Space panel. There are two options to display image space, which are described in greater detail in the results section.

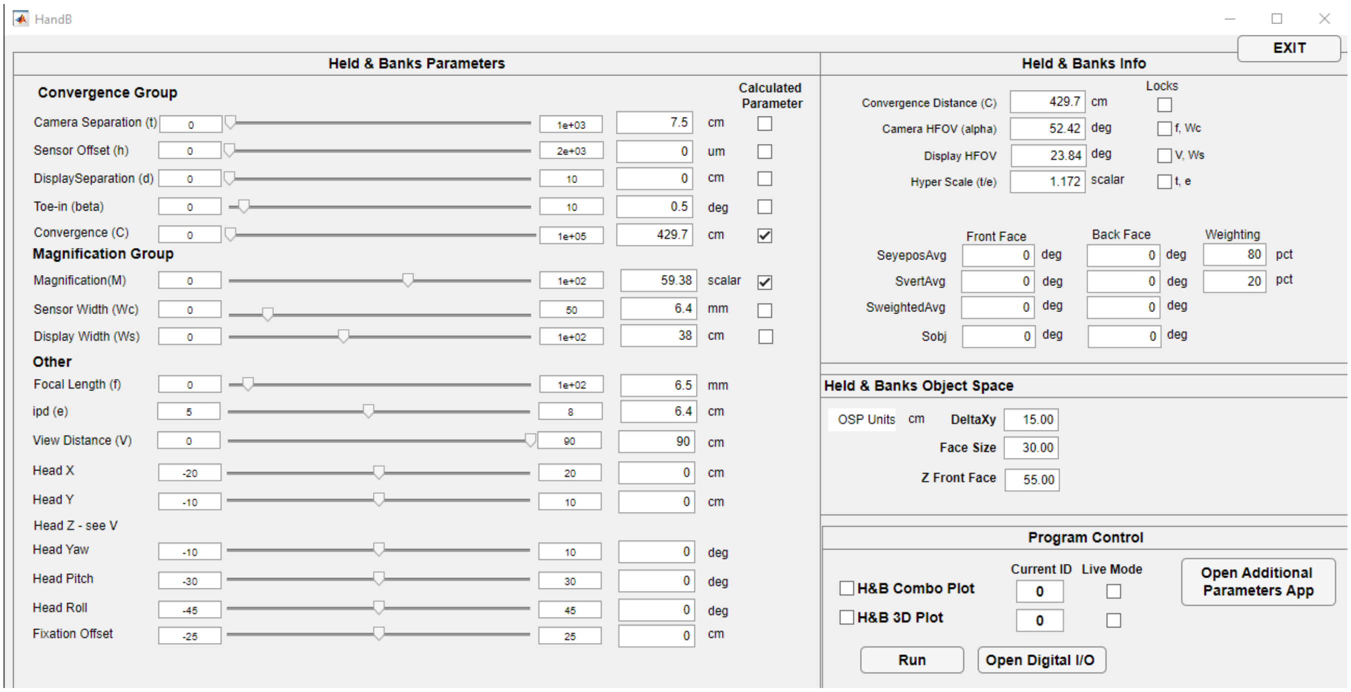

Figure 3. Main Held and Banks Model GUI.

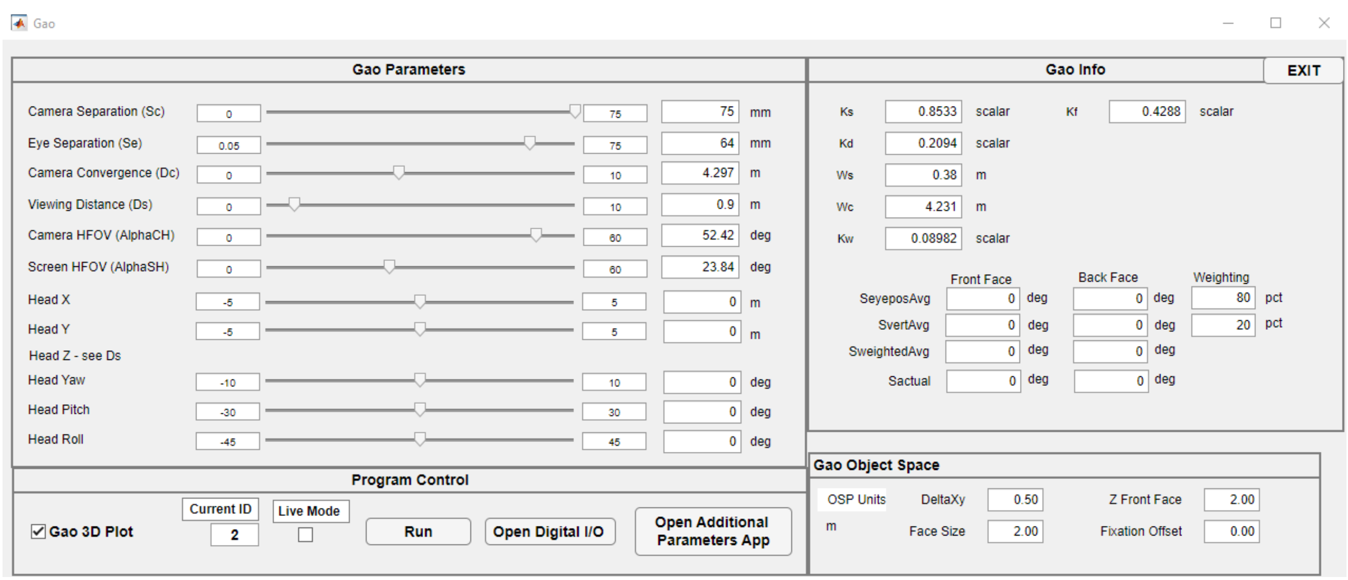

***Figure 4.** Main Gao et al. Model GUI.*

Gao et al. Model GUI

The main Gao et al. model GUI is shown in Figure 4. The parameters and info panels both work the same as in the other two model GUIs. The Gao et al. model is based on ratios, which allows the calculation of image space without knowledge of as many object space specifics as the other models require (e.g., camera toe-in/sensor offset). The outcome variables under the info panel are ratios used in [3]. To see their definitions, the user can hover their mouse over any variable. The slant calculations from the Held and Banks model GUI are also included in this GUI. The Gao et al. model also assumes a cube in object space, which is defined in the object space panel. There is one image space plot available, which is described in the results section. The additional parameters app button brings up the same GUI as in the other two model GUIs, with one tab specific to the Gao et al. graphics. This is also described in the results section.

Results

Here we describe an example stereoscopic display and show the results using the plotting tools of the three different models in the 3DDM tool. The camera input variables are as follows: 75 mm separation, 0.5 degrees camera toe-in, 6.5 mm focal length, and 6.4 mm sensor width. The user viewing distance is 0.9 m and display width is 0.38 m. Inter-pupillary distance is set at 64 mm. This puts the convergence distance at 4.297 m, the camera and display horizontal field of views at 52.42° and 23.84° respectively, and results in a hyperstereo ratio of 1.17.

The Woods et al. model plot depicting the image space is shown in Figure 5. The grid is comprised of 10 cm squares in object space now represented in image space, hence the axes are in image space coordinates. The numbers in red represent the corresponding depth in object space coordinates for comparison. While Figure 5 shows the output graph, the Woods et al. model plot GUI includes several more features. For example, there is a Feature On/Off panel, which allows the user to toggle the object space coordinates on and off using the button ‘Zos Ticks’. The other options in this panel include the options to show fofix contours at 0.3 and 0.5 D, refueling envelopes, and aircraft outlines. The Surface Data panel allows the user to choose to show the grid lines only, percent depth compression, or diopters of fofix mismatch across image space. The Data Point management panel, when ‘Enable’ is selected and the user clicks anywhere in the plot, will load a new window with specific information about that point including the image and object space axes, depth compression, fofix mismatch, divergence, dipvergence and left/right eye screen separation. Multiple data points can be selected, but the information will only apply to the latest point. ‘Erase Markers’ will clear all data points from the figure. Other areas in the figure window allow the user to change the plot axes, plot title and surface data color map. To save the plot as a figure, the user can press the ‘Open Digital I/O’ button, select the output folder, and press ‘Export App’.

The Held and Banks model GUI offers two different ways to plot image space results: referred to as a combo plot, and a 3D plot. Like the published paper, the change from object to image space is shown through the transformation of a cube, first defined in object space. This is done in the main GUI in the object space panel and described in the methods section. Selecting the H&B Combo plot opens another GUI depicting the front and back cube surfaces in both retinal coordinates and image space coordinates (Figure 6). All variables are calculated assuming the viewer of the RVS is fixated at the center of the front surface of the cube. There are more options in the Surface Data panel in this GUI, including divergence, dipvergence, and horizontal and vertical disparity. Also available is a vector field on/off toggle, which displays arrows on the retinal plots depicting corresponding points on the left (arrow heads) and right (arrow tails) retinas of the viewer. Pressing the ‘expand’ button on any of the four figures opens a new window with a larger image of only that figure. From there, data points can be enabled, the same as in the Woods et al. model plot GUI.

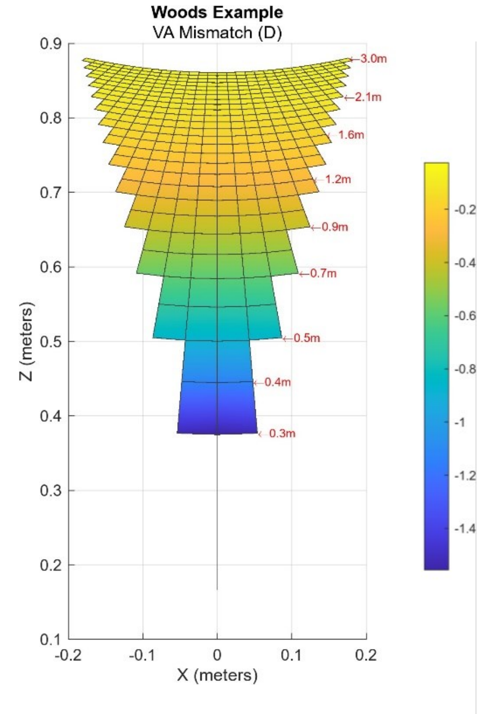

Figure 5. An example of Woods et al. model imagery for the display parameters described. The numbers in red represent the equivalent depth in object space. The color gradient on the right represents the amount of VA mismatch in diopters.

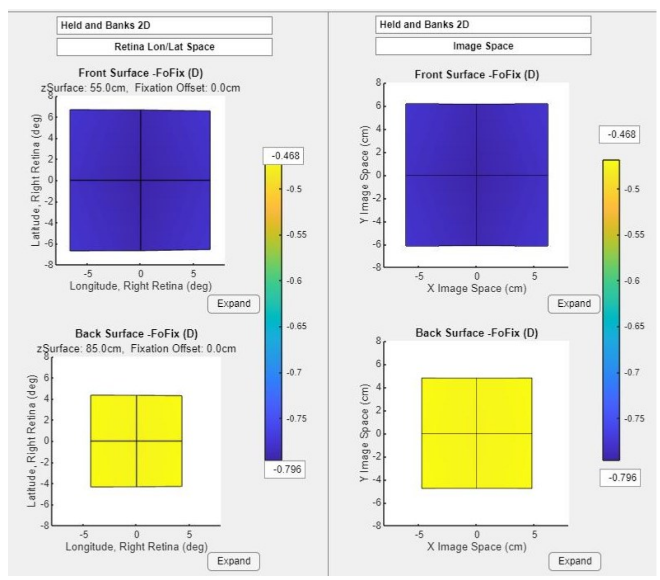

Figure 6. An example of the Held and Banks model imagery in 2D for the display parameters described. The front and back surfaces represent the surfaces of a cube. The imagery on the left is in retinal coordinates (deg) and the imagery on the right is in image space (cm) coordinates. The color gradient on the right represents the amount of VA mismatch in diopters.

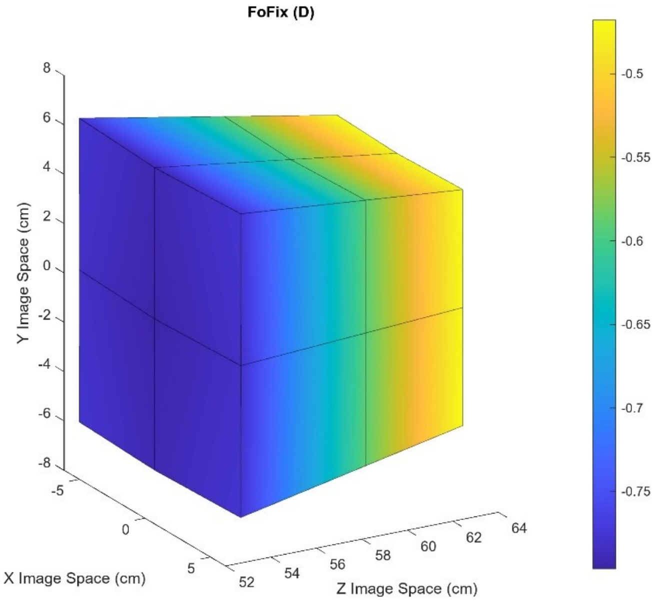

Figure 7. *An example of the Held and Banks model imagery in 3D for the display parameters described. The color gradient on the right represents the amount of VA mismatch in diopters.*

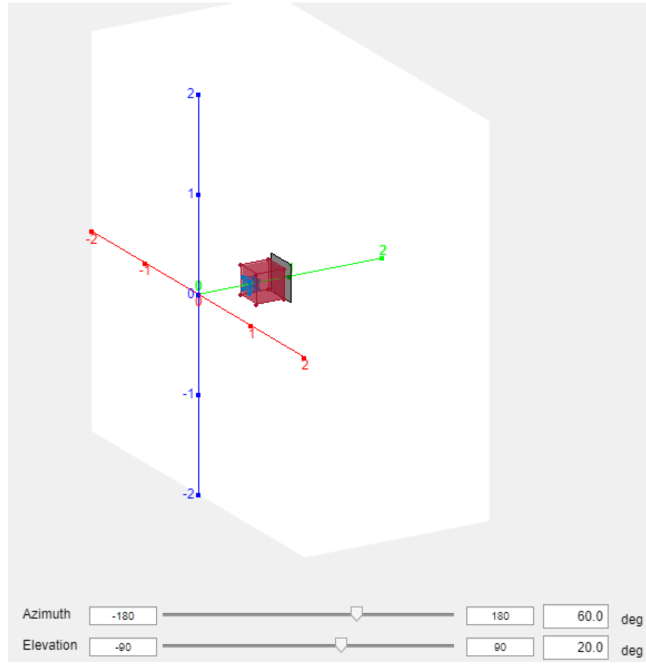

Figure 8. *An example of the Gao et al. model imagery for the display parameters described. The red cube represents the object space cube, the black outline represents the display screen, and the blue "cube" represents the transformation in image space.*

The second Held and Banks plot option is the H&B 3D plot. It displays the 3D cube in image space (see Figure 7). To show the cube from different angles, click and drag directly on the plot. The same surface data variables are available. The user can also use the 'Select Panel' panel to show only one face of the cube in the 3D plot or show one face of the cube in 2D if they want to use the data point function. Both of the Held and Banks GUIs also have options for plot titles, surface data color maps, and saving the figures.

The Gao et al. model 3D imagery is plotted in ratios. It displays the original (object space) cube, the distorted (image space) cube, and the display screen all in one plot, as shown in Figure 8. These three can all be toggled on and off. Like the H&B 3D plot GUI, the Gao et al. 3D Plot GUI contains both the Surface Data panel and the Select Data Panel. These apply only to the image space cube, as shown in Figure 9. Plot titles, axis changes, color maps, and figure saving abilities are all available. The Additional Parameters GUI (as described in methods) has a tab called Gao Graphics. In this tab, the user can specify the axis limits, viewing angle, and the color/transparency for all parts of the plot.

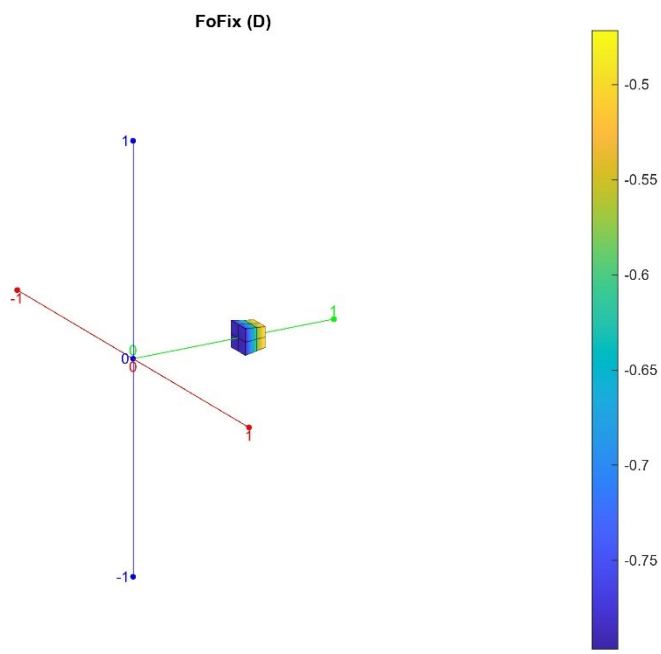

Figure 9. *An example of the Gao et al. model imagery for the display parameters described. Zoomed in for a clearer view of the image space cube only. The color gradient on the right represents the amount of VA mismatch in diopters.*

Conclusion

This new 3D distortion modeling tool allows the user to enter design parameters and provides both quantitative and qualitative information of the resulting perceptual space. Results are based on three different models from vision research literature. The user can also set image space specifics to their desired values and determine what design parameters are needed. Different output options are available for the user to choose from for the resulting image space representation to suit their inquiry. This software allows designers and researchers to actively explore the perceptual effects of stereoscopic display design.

Disclosures

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Author Biography

Eleanor O'Keefe received her BS in biopsychology from the University of California, Santa Barbara (2010) and her PhD in experimental psychology from the University of Louisville (2017). Since then, she has worked in the Operational Based Vision Assessment Lab at Wright-Patterson Air Force Base in Ohio. Her work has focused on visual perception and human factors concerning advanced 3D technology design.