Supplementary Information:
Accommodation-Invariant Computational Near Eye-Displays

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In this document we provide additional discussion and results in support of the primary text. Supplementary Appendix A presents extended captures showing conventional and depth-invariant point spread functions for several different accommodation-invariant display modes. Supplementary Appendix B includes additional results captured from the prototype display. Supplementary Appendix C includes physically accurate optical simulations of alternative accommodation invariant displays.

A Additional Details for Display Calibration

The primary text shows one-dimensional plots for several accommodation settings of conventional near-eye displays and the proposed accommodation-invariant displays. Figure S.1 shows additional RAW photographs of a small region of the display screen with the camera focused at several distances. As expected, the conventional display creates a point spread functions (PSF) that strongly varies in depth. The conventional mode places the display in focus at 1 D (at 1 m). Please note that changes in blur size are linear in diopters, which is the reason we label distances primarily as diopters instead of meters. The PSF created by a focal sweep are nearly depth-invariant. The implemented focal sweep is theoretically valid for a range of 0–3 D, but in practice we observe some imperfections around the closest point (3 D). This is due to the fact that focal sweeps only create an *approximately* depth-invariant PSFs. Most importantly, we observe that the depth invariant PSFs are significantly bigger than the best-focused PSF of the conventional display. As discussed in the primary text, this can be partly mitigated using a multi-plane approximation to a continuously depth-invariant PSF. We demonstrate results captured from the prototype display, in strobed LED backlight mode, for this display configuration using two planes and three planes. At these planes (1 and 3 D for the two-plane mode and 1, 2, and 3 D for the three-plane mode), the results are only marginally degraded compared with the best-focused plane of the conventional display. In between these depth-invariant planes, however, the PSF grows to larger sizes. All capture settings are similar to those described in primary Section 4.

Figure S.2 also shows the spatially-varying PSFs for each display mode over the entire screen. This figure mostly demonstrates that the PSFs are roughly spatially-invariant, although slight lens aberrations create some coma on the periphery of the display. We recommend viewing these images on the monitor and zooming in.

Figure S.3 shows the modulation transfer function (MTF) measurements for the conventional mode (focal plane at 1 D), continuous AI mode, AI 2-plane mode (focal planes at 1 D and 3 D), and AI 3-plane mode (focal planes at 1 D, 2 D, and 3 D). Each plot corresponds to the MTF measured with a camera focusing to a different distance (indicated by the title of each plot).

B Additional Results

Figures S.4 to S.8 show extended results for five different scenes. All images are photographs captured from the prototype at different focus settings (as indicated). Focusing the camera in these experiments results in a small change of image magnification. For the conventional display, the focal plane is at 1 m as indicated by the green outline. Rows 2 and 3 show the depth-invariant display with no with deconvolution applied to the target image and deconvolution implemented, respectively, as described in the primary text. We show the unprocessed results in row 2 mostly for directly comparison of what the deconvolution is able to achieve; without deconvolution (row 2), the image is nearly depth-invariant but blurry. The deconvolution is necessary to restore image quality as best as possible (row 3).

In addition to the accommodation-invariant display mode implemented by a continuous focus sweep (rows 2 and 3), we also show the version that only uses the multi-plane approximation of accommodation-invariance in rows 4 and 5 of figures S.4 to S.8. As expected, the image is sharpest at the respective planes (indicated by green boxes) but the PSFs in between these planes is unconstrained.

Figures S.8 is probably the most challenging example, because it is not a natural image but entirely comprised of high-contrast step edges with very saturated colors. One would not expect the deconvolution to be able to provide a huge benefit over the unprocessed image in this case, simply because the limited dynamic range of the display cannot boost pixel values more than the target image. In this case, a slight reduction of image contrast would help to restore some image frequencies, but we did not attempt this to clearly highlight the limitations of the proposed accommodation-invariant display technology.

We recommend viewing these images on the monitor and zooming in.

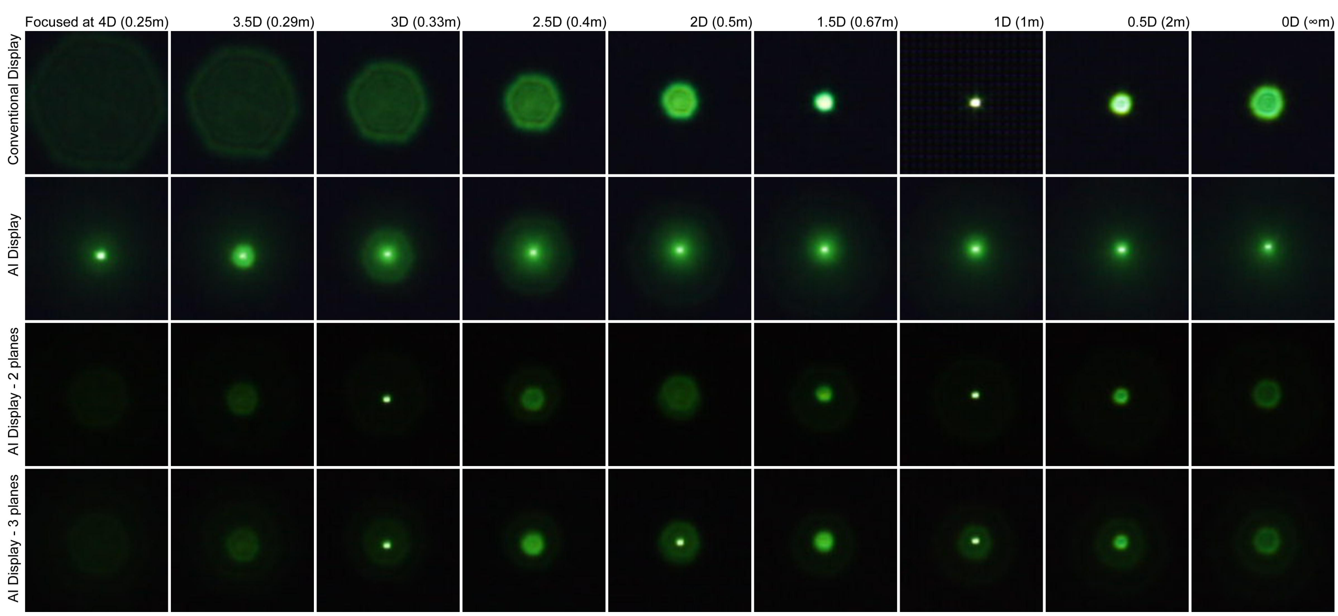

Figure S.1: *Closeup of point spread functions for each of the display modes (green display color channel). Photographs are captured with the same exposure time. Intensity differences are due to the spread of light within PSFs.*

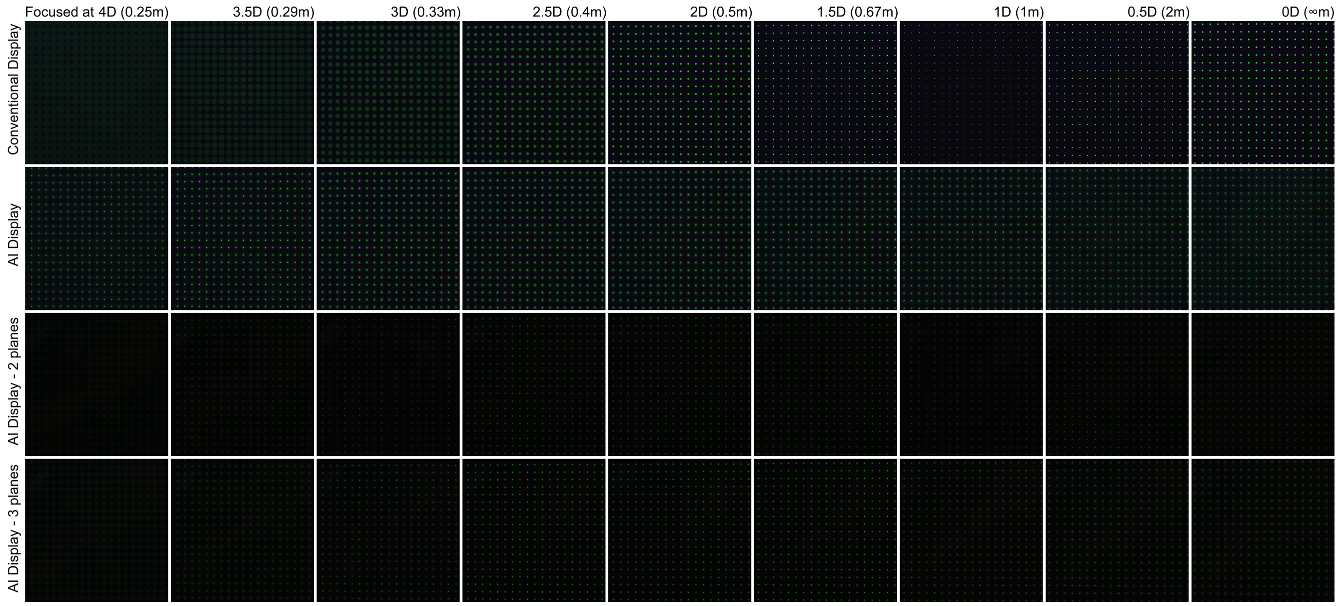

Figure S.2: *Extended results for spatially-varying point spread functions over the display for each of the display modes. Please zoom in.*

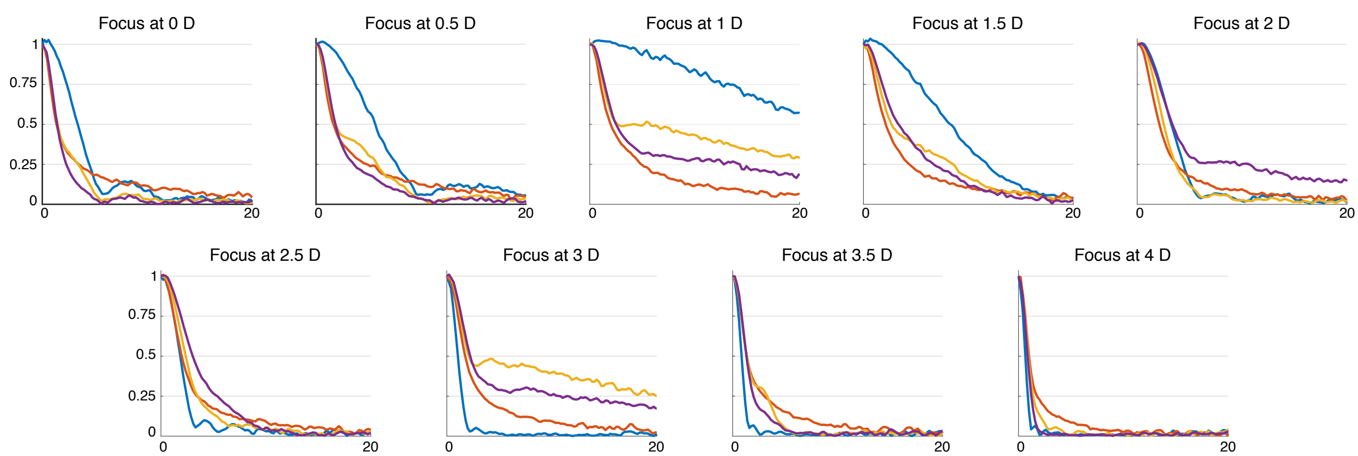

Figure S.3: *Extended results for MTF measurements over a 4 D range of camera focus distances.*

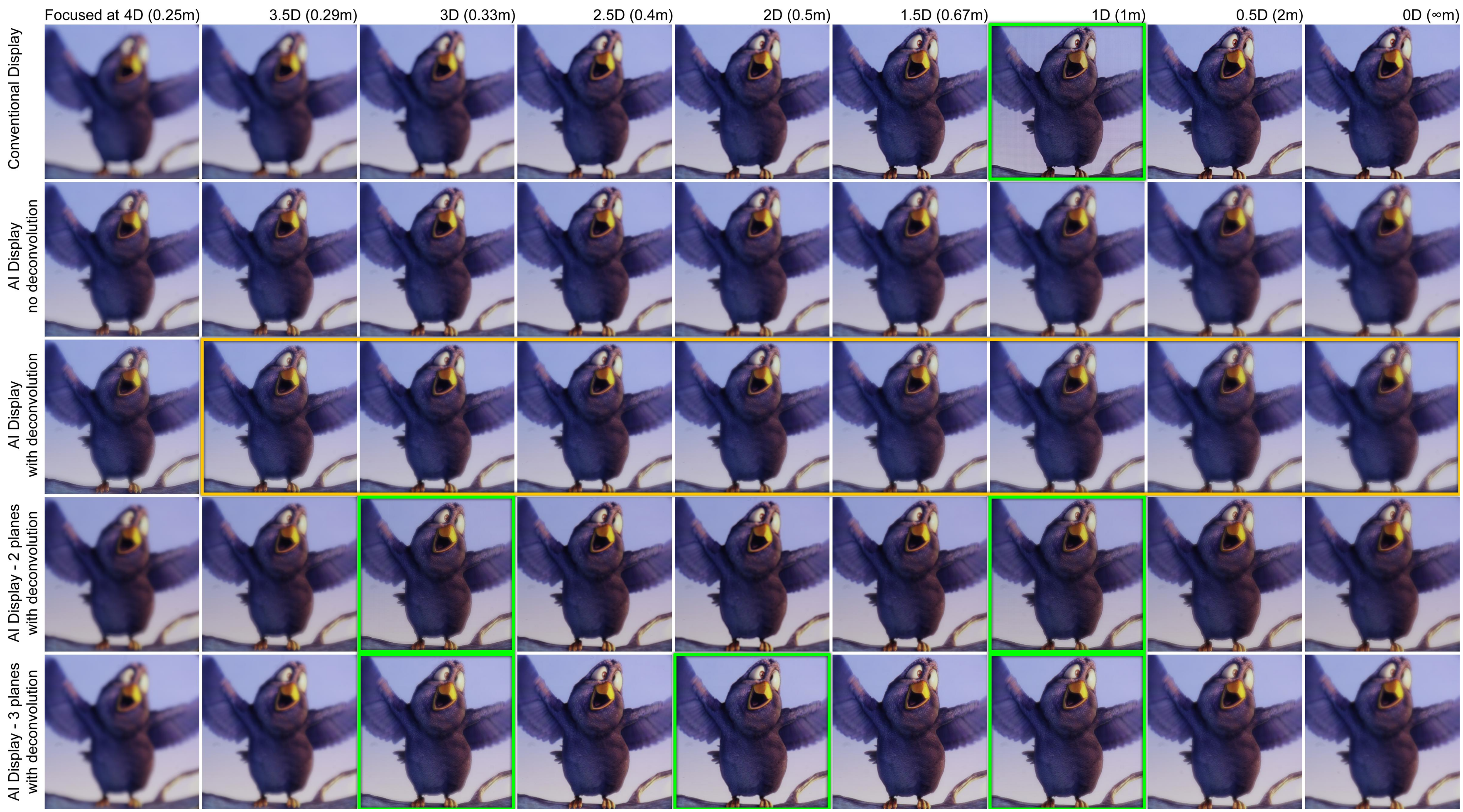

Figure S.4: *Extended results for the "Bird" scene.*

Figure S.5: *Extended results for the "Library" scene.*

Figure S.6: *Extended results for the "Spy Room" scene.*

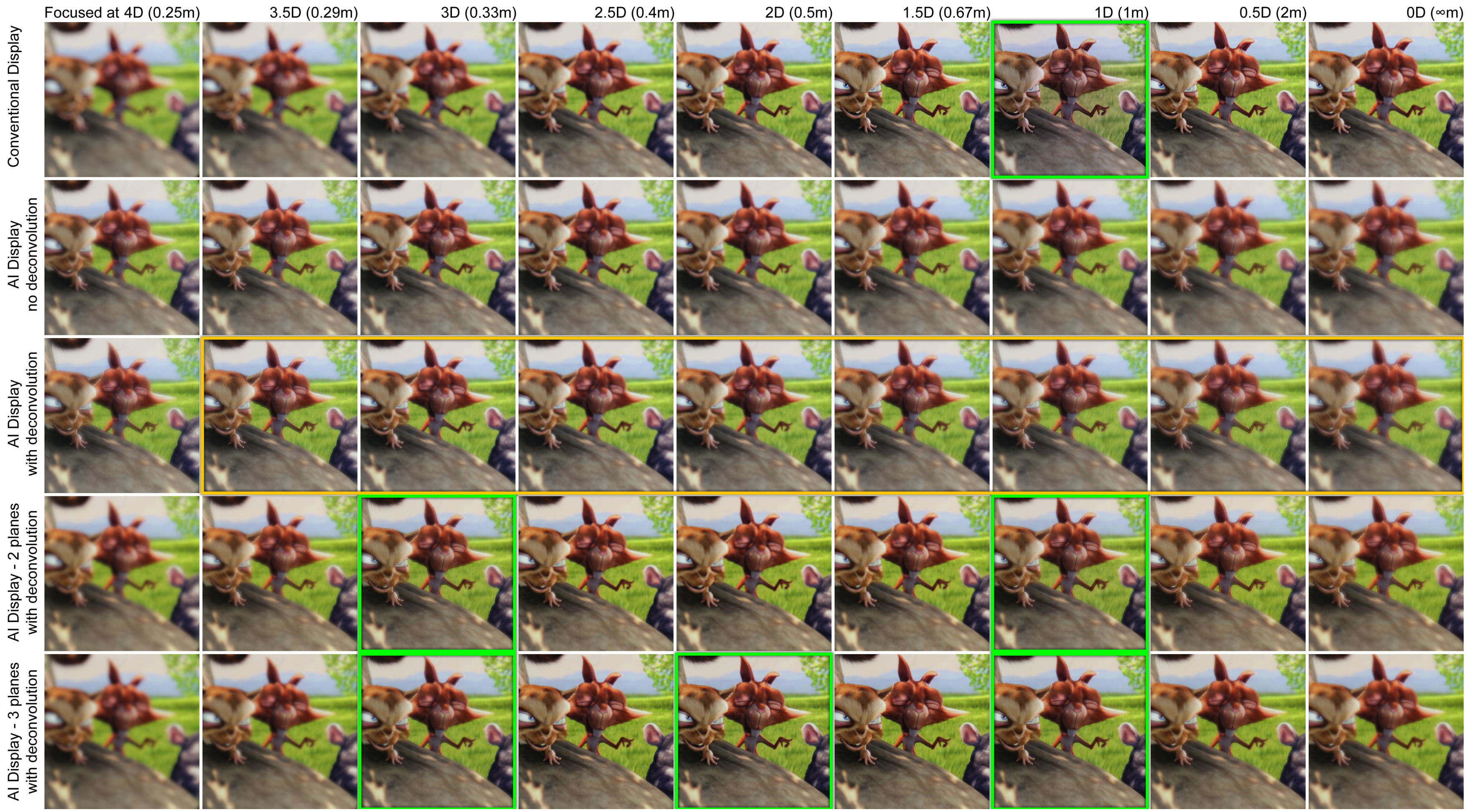

Figure S.7: *Extended results for the "Rodents" scene.*

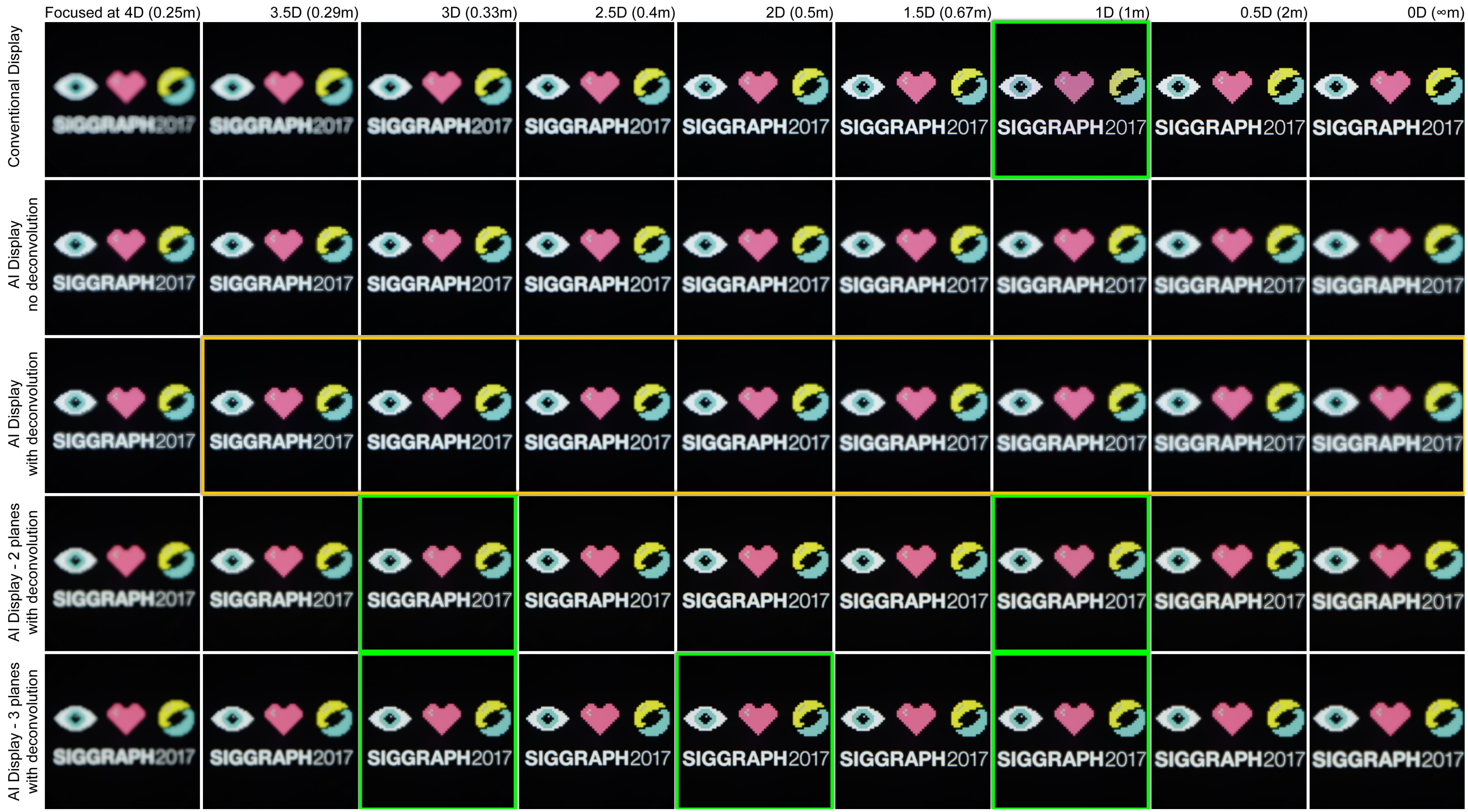

Figure S.8: *Extended results for the "SIGGRAPH" scene.*

C Simulations of Different Optical Implementations

In Figure S.9 we show physically accurate simulations illustrating the trade-offs inherent in other accommodation-invariant display designs that do not have to be made with the focal sweep approach we implemented. Diffraction simulations were carried out with Zemax Optics Studio, using the image simulation tool with diffraction propagation.

A Snellen chart was placed at a distance of 2 meters and sized appropriately for metric readout, where the 20/20 line corresponds to regular 20/20 human vision. Simulations were performed for various accommodation states of the eye, including at 10 m, 2 m, 1m, 0.5 m, 0.25 m and 0.17 m. For the conventional display case (upper row), we assume an eye pupil diameter of 3.18 mm.

For the pinhole display cases, the pupil diameter is restricted by a pinhole to 1 mm, 0.5 mm and 0.05 mm. As can be seen in Figure S.9, the use of a pinhole to increase the accommodation range requires a trade-off with light throughput. The 1 mm diameter pinhole still has a limited accommodation range given by the depth of field. The 0.5 mm diameter pinhole achieves a decent accommodation range, but at the expense of light throughput. The upper right half of the Snellen charts illustrates the unscaled brightness, while the lower right half illustrates the scaled (for visualization purposes) brightness. Furthermore, the accommodation range can only be increased so far before diffraction begins to limit the perceivable resolution, as illustrated by the 0.05 mm diameter pinhole.

For our proposed accommodation-invariant display using a focal sweep (bottom row), we approximate a continuous focal sweep by simulating 100 discrete focal states ranging from 0.2 m to ∞ m with a uniform diopter spacing. The Snellen chart image simulated for this case is deconvolved with the point spread function of a focal sweep corresponding to a 0.5 m accommodation state. The results illustrate that the focal sweep ensures a good accommodation range from 10 m to 0.25 m, but that at 0.17 m (right-most column), which is outside of the focal sweep range for the point spread function used for deconvolution of the displayed target, the target is no longer perceived to be in focus. Importantly, the full 3.18 mm eye pupil is utilized, so there is no loss in light throughput compared with the pinhole display cases. The focal sweep produces both the best accommodation range and light transmission efficiency.

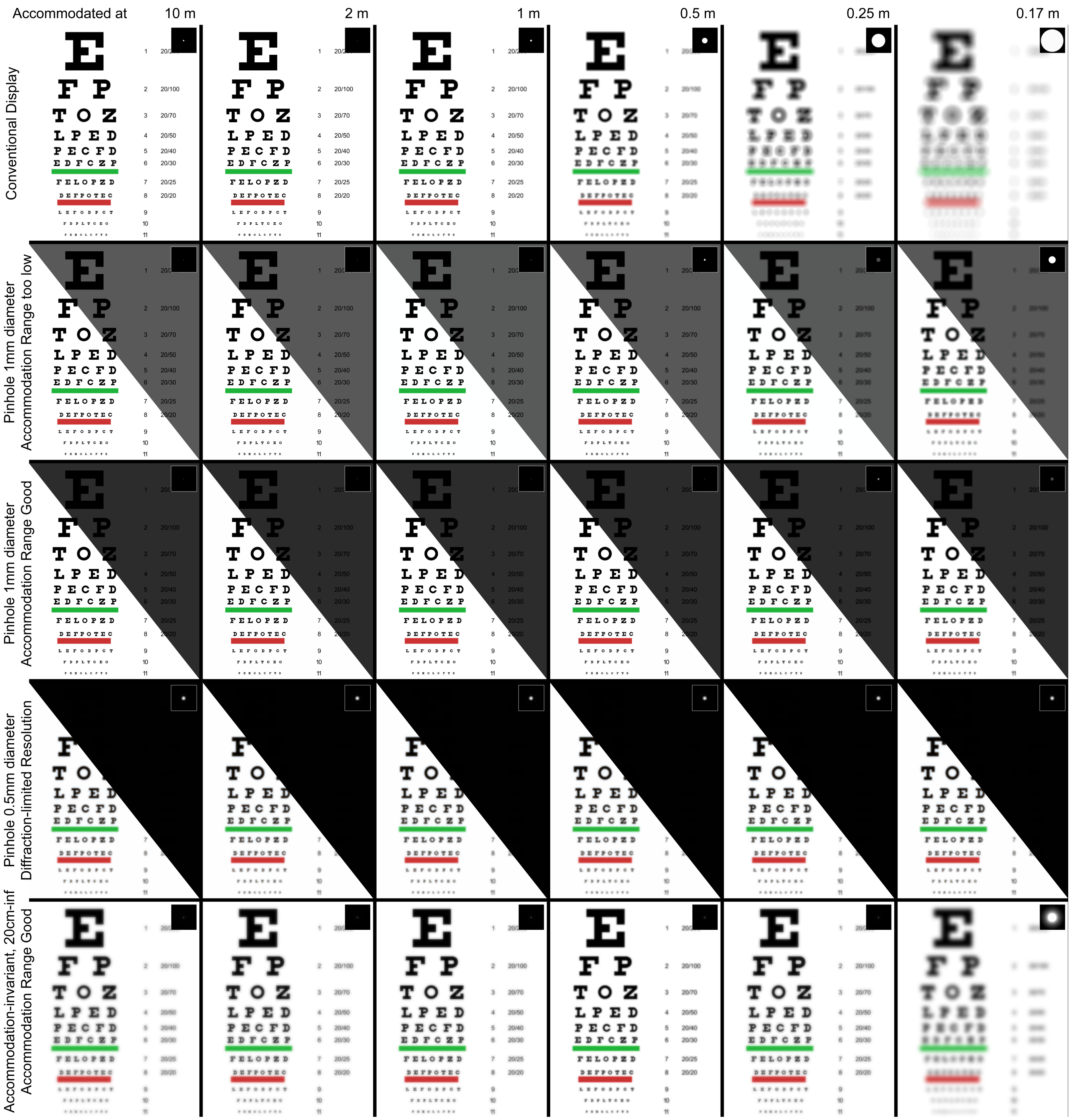

Figure S.9: *Simulated point spread functions (upper right insets, magnified 2x) and Snellen chart for a chart placed at 2 meters and viewed with various accommodation states (columns). A conventional display (first row) has a limited accommodation range. Reducing the aperture with a pinhole (next three rows) requires reducing light transmission to achieve a good accommodation range. The accommodation-invariant focal sweep display (last row) yields a good accommodation range while preserving light transmission.*