A 100,000-to-1 high dynamic range (HDR) luminance display for investigating visual perception under real-world luminance dynamics

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ABSTRACT

Background: Real-world illumination challenges both autonomous sensing and displays, because scene luminance can vary by up to $10^9$-to-1, whereas vision models have limited ability to generalize beyond 100-to-1 luminance contrast. Brain mechanisms automatically normalize the visual input based on feature context, but they remain poorly understood because of the limitations of commercially available displays.

New method: Here, we describe procedures for setup, calibration, and precision check of an HDR display system, based on a JVC DLA-RS600U reference projector, with over 100,000-to-1 luminance dynamic range ($636 - 0.006055$ cd/m²), pseudo 11 bit grayscale precision, and 3 ms temporal precision in the MATLAB/Psychtoolbox software environment. The setup is synchronized with electroencephalography (EEG) and infrared eye-tracking measurements.

Results: We show display metrics including light scatter versus average display luminance (ADL), spatial uniformity, and spatial uniformity at high spatial frequency. We also show a luminance normalization phenomenon, contextual facilitation of a high contrast target, whose discovery required HDR display.

Comparison with existing methods: This system provides 100-fold greater dynamic range than standard 1000-to-1 contrast displays and increases the number of gray levels from 256 or 1024 (8 or 10 bits) to 2048 (pseudo 11 bits), enabling the study of mesopic-to-photopic vision, at the expense of spatial non-uniformities.

Conclusions: This HDR research capability opens new questions of how visual perception is resilient to real-world luminance dynamics and will lead to improved visual modeling of dense urban and forest environments and of...
1. Introduction

1.1. HDR displays enable research to understand contextual processing under real-world illumination

Vision is an inherently ambiguous process of estimating 3D shape and object identity from weak reflectance signals, that can be several orders of magnitude weaker than variations in illumination (Gilchrist et al., 1999). The apparent ease of vision is due to brain mechanisms which estimate reflectance and shape by leveraging contextual cues from the scene to untangle the many factors that contribute to luminance, including illumination, surface slant, atmosphere, surface albedo, glossiness and roughness. Investigating the brain’s visual mechanisms under high dynamic range luminance is necessary to develop models, including appropriate compression and tone remapping of the mechanisms under high dynamic range luminance is necessary to develop models, including appropriate compression and tone remapping of the image, to improve both machine sensing and displays to improve performance in real-world contexts (Borel-Donohue and Young, 2019; Harrison et al., 2019).

Historically, the unavailability of HDR displays has been a primary impediment to understanding how the brain processes real-world luminance, underlying a major gap between biological and machine vision. Early efforts to understand HDR vision were based on hand-constructed scenes (Zdravković et al., 2012), and it was only recently that computerized displays became available for more sophisticated studies. A few studies have used custom-developed stacked LCD displays or related methods for HDR (Olkkonen and Brainard, 2010; Radonjic et al., 2011b, but such systems are difficult to replicate and lack sufficient spatial resolution and uniformity for our studies. Commercial and research displays are typically limited to less than 1000:1 luminance contrast ratio and 8–10 bit depth, i.e. 256–1024 shades of gray.

Here, we describe the setup, calibration, and precision testing of a system with over 1000:1 luminance contrast ratio and pseudo 11 bit depth (2048 shades of gray), enabling the study of the visual system’s HDR luminance normalization processes.

2. Methods

2.1. HDR display

All images were projected from a JVC DLA-RS600U 4K Reference Projector software version u83.2, PS version 100310 and displayed bioculally on an HD projection screen. Contour screen with HD surface, ‘HD Progressive 1.1’, gain = 1.10 at 0° and 1.00 at 20°, half angle = 85°, gloss at 75° = 24, color shift at 60° = 3 %). To maximize the contrast ratio, the projector was set to the smallest zoom and the following settings, based on the JVC instruction manual and the JVC website (JVC, 2019): Color Profile ‘Reference’, Color Temp ‘6500K’, Gamma ‘0’, MPC Level 4K e-shift ‘ON’, Original Resolution ‘Auto’, Enhance ‘0’, Dynamic contrast ‘0’, Smoothing ‘0’, NR ‘0’; Blur Reduction Clear Motion Drive ‘High’, Motion Enhance ‘Off’, Contrast ‘0’, Brightness ‘0’, Color ‘20’, Tint ‘-5’, Input ‘HDMI-1’, Source ‘1080p 60’, Deep Color ‘12 bit’, and Color Space ‘RGB’. “Gamma D”, in particular, is the manufacturer’s recommended setting for HDR that better displays the full logarithmic range by allocating more bits to the lower and middle ranges. Although the projector, graphics card, and HDMI cable supported 12-bits-per-channel bit depth, the overall system was software-limited by Psychtoolbox to 10.7 bit depth, because all the color information needs to fit into 32 bits. Images spanned 1920 × 1080 pixels in resolution (48.7 × 27.3 cm w × h) and were observed from a chinrest-stabilized viewing distance of 78 cm, thus spanning 34.7° × 19.9° viewing angle with pixel size 0.0181° × 0.0184°. Gaze and pupil size were tracked monocularly via an infrared eye tracker (EyeLink 1000 Plus), and 64-channel EEG was measured...
using a Biosemi Active Two system, all synchronized via Lab Streaming Layer software (Swartz Center for Computational Neuroscience, UCSD) (Kothe, 2014; Tanaka et al., 2018) (Fig. 1B).

Images were displayed at 60 Hz and pseudo 11 bits (10.7 bits, i.e. 11 bits red, 11 bits green, but only 10 bits blue) precision via a framebuffer procedure using Psychotoolbox 3.0 (Kleiner et al., 2007) for GNU/Linux X11 software (version 3.0.14 – Build date: May 8, 2017) running under MATLAB 64-bit version 2016b on Ubuntu 16.04 (seen by Psychotoolbox as Linux version 4.4.0-31-generic). Because higher bit precision in Psycho toolbox 3.0 requires graphics cards supporting the AMD Hawaii PRO GL (DRM 2.43.0 / 4.4.0-31-generic, LLVM 3.8.0) (Kleiner, 2017), i.e. the Radeon/Fire cards of the “Sea Islands” family (after 2014), we used the AMD FirePro W8100 graphics card (AMD, 2019). We validated a second system running OSX (Mac Pro 3.2, model A1289, server mid-2010 family) and a FirePro W5100 graphics card. We also tested other graphics cards outside the “Sea Islands” family (VisionTek RADEON R9 280X, MSI Twin Frozr III, and Nvidia Quadro) and found that, as expected, they were limited to 8- or 10-bpc. We used the Psycho toolbox command ‘PsychImaging(‘AddTask’, ‘General’, ‘EnableNative11Bit-Framebuffer’) to disable and bypass the hardware’s Gamma color lookup table (‘clut’) and switch the framebuffer into 11 bpc mode.

2.2. Luminance stability after cold start

We characterized the projector’s luminance stability after cold start by measuring the luminance of each primary for at least thirty minutes via a spectrophotometer (Photo Research PR-745). The projector was turned off for at least an hour before testing one primary, then turned off for at least an hour before testing the next primary. With the projector off, the room luminance was 0.000598 cd/m². At cold start, the full screen peak luminances were 149.4 (red), 439.6 (green), and 44.05 (blue) cd/m². After 30 min, the luminances declined to 144.0 (96.4 %, red), 415.2 (94.4 %, green), and 43.79 (99.4 %, blue) cd/m² (Fig. 2). Because of the larger decline of the green primary, we continued measurements to 60 min, where the green primary declined to 413.0 cd/m², 99.5 % of the 30 min value. For all other tests, we warmed up the projector for at least 30 min before making measurements.

2.3. Projector calibration

We calibrated the projector by measuring the luminance of a uniform full screen at over 75 grayscale color indices (setting the RGB primaries to identical values), averaging across 2–5 repeated measurements per color index. To reduce the noise effects of drift, we repeated measured at each grayscale color index before moving to the next color index. We used different photometer settings depending on the light level, measuring smaller 0.5° diameter and 2 nm wide samples for the brightest indices and larger 2° diameter and 4 nm wide samples (and ~15 s averaging per sample) for the darkest indices. To ensure that the calibration was correct for the entire range, we measured more samples at the steepest parts of the curve (e.g. 0.01 to 0.05 cd/m²) and near inflection points. We log-linearly interpolated the luminance for indices that were not measured, and the resulting Gamma curve is plotted in Fig. 3A. On our second platform (OSX), we observed a rightward shift of ~150 color indices in this Gamma curve, which resulted in more dark pixels for the lowest color indices and a smaller range of ceiling effect, but otherwise no change to the Gamma curve. The curve shows a steep rise in luminance for the lowest indices and a ceiling effect, resulting in an effective linearized Gamma range of luminances from 0.006055 to 636.4 cd/m² (u,v = 0.1953, 0.3199; x,y = 0.3200, 0.3494, 6037 K, uncorrected color indices from 16 to 1728) for a maximum contrast ratio of over 100,000:1.

The photometer sampled from the projector screen, rather than directly from the projector output, and this difference may explain why we did not observe the projector manufacturer’s specified maximum contrast ratio of 150,000:1. All tests were with a static projector iris, and we did not assess the manufacturer’s stated capability of 1.5 M contrast ratio with dynamic iris. We note the discrepancy between the calibration peak luminance of 636.4 cd/m² versus the sum of the primary measurements (603.0 cd/m² at 30 min after cold start) and attribute this difference to measurement spatial position, spectral sampling width (4 nm for calibration to avoid photometer saturation, vs. 14 nm for single primary), and lamp aging in the one year interval between the initial calibration and the later cold start and display metrics measurements.

This range spans mesopic vision (0.001–3 cd/m², when both cones and rods are required to support vision) to the lower end of photopic vision (10 to 10⁶ cd/m²), consistent with seeing in mixed indoor/outdoor environments and in twilight e.g. nighttime street and outdoor lighting and aviation lighting. However, we note that with only 3 primaries, the system is unable to isolate rod photoreceptors for mesopic testing because the amount of rod contribution can considerably change human sensitivities in the mesopic range, particularly for dynamic stimulation (e.g. by destructive interference) (Bayer et al., 2015).

2.4. Projection luminance precision

To our knowledge, we are the first to validate the 10.7 bits-per-channel precision of Psycho toolbox 3 via careful photometer measurements, due to lack of suitable display hardware at developer sites. We optimized for both display precision and photometer sensitivity by testing a range of uncorrected color indices (uniform RGB primary values) ranging from 1100 to 1120, at nearly 3/4 of the maximum luminance capability and the smoothest part of the Gamma curve. We measured 5 repeated samples per color index, completing measurements at each color index before moving on to the next, to avoid slow drift effects on repeated measurements. The averaged measurements generally increased steadily, consistent with 10.7 bit precision, without obvious staircase that would indicate 10 bit precision or lower (Fig. 3B).

2.5. Stray light and effective contrast ratio

To determine the sensitivity of the display to stray light within the projector, we measured the luminance of a central white or black disk (1, 2, or 4 deg. diameter disk; 0.5 deg measuring aperture) against a
black background with different degrees of checkerboard density (0 %, 1 %, 2 %, 5 %, 10 %, 20 %, 50 % and 100 % average display luminance ‘ADL’, i.e. the percent of the background occupied by white squares, at square sizes of 10 × 10 pixels, 0.18 × 0.18 deg.). The standard ANSI contrast test pattern corresponds to 50 % ADL and may be a reasonable approximation for the average luminance distribution of early television programs (Quinn and Newman, 1965), whereas 1%–5% ADL better approximates today’s typical movie pictures (Anna and Florian, 2015; stranger89 and Petersen, 2008). Between 0 % ADL (full screen black) and 1 % ADL, the luminance of the black disk increased from 0.0055 cd/m² to 0.104, 0.093, and 0.081 cd/m², for disk diameters 1, 2, and 4°, respectively (Fig. 4A). At 5 % ADL, the black disk luminance was 0.361, 0.303, and 0.253 cd/m². At 50 % ADL, the black disk luminance was 4.14, 3.08, and 2.52 cd/m². At 100 % ADL, the black disk luminance was 10.5, 8.42, and 7.05 cd/m². At fine scale, a very faint stellate pattern is apparent at each square (Fig. 4A insets). The arms of the stellate pattern radiate out at 60° angles for about 0.3° and are not aligned to neighboring squares, indicating that they are a property of the projector rather than tied to the stimulus arrangement.

For the white disks, the luminances were consistently between 576–593 cd/m², reaching 603 cd/m² for 5 % ADL (Fig. 4B). The luminance drops to 301 and 305 cd/m² for 1 and 2 deg. disk diameters, a decline that was visibly obvious. For uniform white screen, the luminance was 570 cd/m². The DLA-RS600U is not advertised with the automatic tonemapping in newer models of JVC’s D-ILA LCoS technology.

Dividing the white-disk luminance by the black-disk luminance yields an effective contrast ratio of 105,000:1 for the 4 deg. diameter disk at 0 % ADL, decreasing to 56,700:1 and 55,900:1 for 1 and 2 deg. disk diameters, respectively (Fig. 4C). The effective contrast ratio is further reduced to 5690:1, 6280:1, and 7170:1 at 1 % ADL; 1590:1, 1990:1, and 2310:1 at 5 % ADL; 139:1, 188:1 and 228:1 at 50 % ADL; and 54.5:1, 67.6:1, and 80.8:1 at 100 % ADL, for 1, 2, and 4 deg., respectively.

2.6. Spatial uniformity

To measure spatial uniformity, we sampled in a crosshair pattern at −12, −6, 0, 6, and 12 deg. horizontal offsets and −6, −3, 0, 3, and 6 deg. vertical offsets. We tested with 1, 2, and 4 deg. disk diameters, for both a white disk against a black background and for a black disk against a white background (Fig. 5). For the 4 deg. white disk, the luminance was 586 cd/m² at the center and decreased to 464 (79 %) and 555 (95 %) cd/m² at 12 deg. left and right and was 627 (107 %) and 568 (97 %) cd/m² at 6 deg. above and below. For the 4 deg. black disk, the luminance was 7.05 cd/m² at the center and decreased to 5.31 (75 %) and 5.86 (83 %) cd/m² at 12 deg. left and right and was 6.43 (91 %) and 5.90 (84 %) cd/m² at 6 deg. above and below. These spatial uniformities are larger than the 9 % decrease expected from the projection screen at 20°.

2.7. Spatial uniformity at high spatial frequency

A possible concern with multi-layer high contrast LCD technologies is that light reflection across the layers can cause spatial non-uniformities at high spatial frequencies. For example, the EIZO CG3145, which is a dual-layer LCD with 4 K resolution, 1000 cd/m², 10-bit, and 1,000,000:1 contrast, has high spatial non-uniformity at high spatial frequency. The JVC RS600U projector’s D-ILA LCoS technology is based on multi-layer LCD that is both reflective and transmissive, so it also raises this concern. We measured the luminance of white lines against a black background at different line widths (1, 2, 5, and 10 pixels, with periodicity of 10 pixels or 0.18 deg. per cycle; i.e. 10, 20, 50, and 100 % ADL), at the same horizontal and vertical offsets and a larger 2 deg. measuring aperture to avoid aliased sampling (to avoid photometer saturation, spectral sampling width is reduced from 14 nm to 4 nm). At 1 pixel width, the luminance at the center of the screen for vertical lines (21.67 cd/m², −62 %) was lower than expected for 10 % ADL (57.0 cd/m², based on 570 cd/m² at 100 % ADL) (Fig. 6A). The percentage deviation was similar across horizontal and vertical positions, ranging from −60.8 % (20.97 versus 53.5 cd/m² expected) at 6 deg. left to −63 % (18.5 cd/m² versus 50.5 cd/m² expected) at 12 deg. right (Fig. 6B).

The luminance deviation was slightly weaker for horizontal lines, averaging −48.2 % at 1 % ADL (range −46.9 % to −49.6 %), but this orientation dependency was not obvious for thicker lines. The percentage deviations were also spatially uniform at 2 pixel width (0.036 deg.), ranging from −47.1 % to −50.7 % across spatial positions and orientations. The percentage deviation was much weaker at 5 pixel width (0.09 deg.), averaging −17.7 % and ranging from −14.1 % to −20.3 % across positions and orientations. At 9 pixel width (90 % ADL, i.e. 1 pixel width black lines against a white background), the deviation averaged −11.0 % and ranged from −3.98 % to −16.3 %. For comparison, 4 cyc/deg. Gabors are suitable for testing V1 receptive fields (Fig. 2 of (Chu et al., 2014)), so each subdomain of the Gabor would be 0.125 deg. (7 pixels) wide, corresponding to an expected decrease of about −13 %.
2.8. Linearity of array test patterns

With these issues of stray light and spatial non-uniformities, we needed to assess the degree to which our experimental stimuli were accurately reproduced on the screen. The core part of our stimuli consists of a 5 × 5 array of 1 deg. gray patches log-linearly spanning 0.4–40 cd/m², with a central patch always at 4 cd/m². Such arrays were previously used to assess spatial effects on brightness perception (Allred et al., 2012; Radonjic et al., 2011a). Fig. 7A shows three examples of such arrays and their measured patch luminances (red, green, and blue lines) compared with the requested luminances (dashed black line), measured by sampling at the center of the screen and shifting the array position sample each patch. The peak luminances were 37.15, 37.05, and 37.21 cd/m², an average reduction of −7.2 % versus the 40 cd/m² requested. The darkest patches were 0.3945, 0.3762, and 0.3921 cd/m², and average reduction of −3.1 % versus the 0.4 cd/m² requested. On average, the actual luminances deviated from the requested luminances by −7.8 % (range −12.4 % to +1.9 %) and were brighter-than-average at the darker patches (Fig. 7B).

2.9. Display timing delay

To measure the timing offsets and precision between the Matlab task control timestamps and when the images were actually updated on the projection screen, we ran a test block (398 trials) with a photodiode pointed towards the projector, positioned in the background part of the image just below a test stimulus (a 5 × 5 array, see below). The output of the photodiode was sent to Lab Streaming Layer via a custom Arduino device (Jaswa et al., 2012; Lance et al., 2013). Comparing the timestamp of when the code was executed to display the blank screen, to the time at which the photodiode registered the increase in luminance, showed an average projector display lag of 137 ± 2.8 ms. A similar comparison, this time for the blank ‘off’ (background darkening immediately followed by array and target onsets) showed an average lag of 162 ± 4.9 ms. This difference of 24.4 ± 1.5 ms, just over one video frame at 60 Hz frame rate, is task-specific, due to two additional Matlab image updates for the array and target sent at blank offset.

2.10. An example of a luminance normalization phenomenon requiring HDR display

This ability to display high resolution HDR images allowed us to investigate how luminance normalization and fine contextual features are mechanistically linked in naturalistic visual perception. Here, we show an example of a strong contextual effect of abrupt darkening on orientation discrimination, as might occur when scanning from brighter...
to darker regions of a real-world scene. The experiment was conducted in the MIND lab at the Army Research Laboratory at Aberdeen Proving Ground, MD, according to a protocol approved by the Army’s Human Research Protection Program.

Based on single neuron receptive field properties in V1, we speculated that at least 10,000:1 contrast ratio and better than 0.06° pixel resolution (half the 0.125 deg. width of a subdomain of a 4 cyc/deg. Gabor) would be required to observe HDR-specific interactions between luminance and orientation processing in our task. This requirement is beyond the capabilities of standard displays but is well within the 100,000-to-1 contrast ratio and 0.018° pixel resolution of our HDR display system.

Previous reports of contextual orientation effects found that flankers drive a facilitating response (making a co-oriented target easier to detect) if the target were low contrast, but that this effect becomes suppressive at higher target contrast. Both facilitation and suppression have been attributed to the balance of local recurrent excitatory and inhibitory mechanisms in V1, but they have thus far only been investigated for static luminance displays and uniform patch luminance (Chen et al., 2001; Chen and Tyler, 2001, 2002; Li, 1998, 2011; Polat et al., 1998; Polat and Sagi, 1993, 2006).

We tested the effect of luminance dynamics on contextual facilitation/suppression via a two-alternative forced choice (2AFC) task in which subjects report the orientation of the stronger of two Gabor targets shown at the center of a 5 × 5 array (Fig. 8A top). By manipulating the magnitude of abrupt darkening, testing a range of target contrast mixtures, and fitting the behavioral responses with a psychometric function, we were able to determine whether the flankers induced a facilitatory or suppressive/assimilation effect under naturalistic luminance dynamics.

Each trial began with an adapting blank screen of 400, 40, or 4 cd/m² for at least 500 ms (Fig. 8A bottom). To maintain a constant peak luminance in the visual field, all trials included static 400 cd/m² ‘light anchors’ (Gilchrist et al., 1999) sized 1° × 1° at the four corners of the screen. Following a keypress, the blank background was replaced by a black screen (0.006 cd/m²) and a 4 cd/m² target patch at the center of a 5 × 5 array of 1° × 1° flanker patches ranging from 0.4–40 cd/m². Each patch contained a Gabor whose pixels spanned 0.1× to 10× its patch luminance, and the target was a contrast mixture of two Gabors. This combination of adapting blank screen, patches, and Gabors resulted in a total luminance range of up to 10,000-to-1. The subject reported the orientation of the stronger target Gabor via arrow key.
We tested two flanker conditions and five target contrast mixtures (30/70, 40/60, 50/50, 60/40, 70/30 % A/B). For both target and flankers, orientation ‘A’ indicates Gabor orientation 45° (tilted right) and ‘B’ indicates 135° (tilted left). To examine how contextual luminance and orientation combine to affect target discrimination, we manipulated the conjunction of luminance and orientation across the 5 × 5 array of patches. We defined flankers of interest (Fig. 8B, red lines) as the 12 flanker patches that are most similar in luminance to the target. The flankers of interest are oriented either 45° (Flankers ‘A’) or 135° (Flankers ‘B’) depending on the flanker condition. The remaining 12 flankers are of the opposite orientation (Fig. 8C). The positions and orientations of the flankers were balanced and pseudorandomized across trials.

Fig. 9A shows an example of how this conjunction of luminance dynamics and flanker orientation affects orientation discrimination for one subject AH. With 100× darkening (from a 400 cd/m² adapting blank screen to the 4 cd/m² target patch), subject AH’s perceptual report of the target orientation depended strongly on flanker condition. The difference in perceptual report between flanker conditions A (red) and B (blue) is equivalent to an 18 % difference in target contrast mixture, based on the difference at the 50 %-choose-A threshold (p < 0.01).

Surprisingly, the direction of bias was toward the orientation of the flankers of interest, consistent with facilitation, even though the high contrast of the targets would have predicted a suppression effect. Subject AH also showed a weak facilitation effect of 7.7 % threshold bias (p < 0.05) for the 40 cd/m² adapting blank (Fig. 9B), and no significant bias for the 4 cd/m² adapting blank (Fig. 9C). These results were consistent across 9 subjects, averaging 14.8 % (p = 0.0003, two-tailed t-test), 3.1 % (p = 0.016), and − 0.06 % (p = n.s.) threshold bias for the 400, 40, and 4 cd/m² adapting blank conditions, respectively.

3. Conclusion

We developed an HDR display research platform with improved characteristics of over 100,000:1 contrast ratio and pseudo 11 bits grayscale, versus standard SDR displays that are typically limited to 1000:1 contrast ratio and 8–10 bits. We characterized the display in terms of stray light, spatial uniformity, and spatial uniformity at high spatial frequency and show that the system maintains over 1000:1 contrast ratio at up to 5 % average display luminance (ADL) that is typical of today’s movie pictures. This advance allowed us to discover new phenomena linking contextual mechanisms to luminance normalization and target discrimination. These results advance our capability to develop resilient and intuitive real-world machine vision and to develop naturalistic mixed indoor/outdoor displays, such as for augmented reality and for cockpits, by discovering the brain’s HDR luminance normalization mechanisms.

CRediT authorship contribution statement

Chou P. Hung: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. Chloe Callahan-Flintoft: Methodology, Software, Validation, Investigation, Writing - review & editing. Anthony J. Walker: Software. Paul D. Fedele: Validation, Investigation, Writing - review & editing. Kim F. Fluitt: Validation, Investigation, Writing - review & editing. Onyekachi Odoemene: Software, Formal analysis, Investigation. Andre V. Harrison: Conceptualization. Barry D. Vaughan: Validation, Investigation. Matthew S. Jaswa: Software, Validation. Min Wei: Validation, Investigation, Writing - review & editing.
Fig. 9. Example of a perceptual bias discovered via HDR display. (A) When a 400 cd/m² adapting blank screen was followed by the HDR array and 4 cd/m² target (100 × darkening), Subject AH’s perceptual report was strongly biased toward the orientation of the flanker of interest. This bias is based on the difference between Flanker A (red) and Flanker B (blue) conditions, showing a stronger tendency to report the target as ‘A’ when the flanker of interest was also ‘A’, and to report the target as ‘B’ when the flanker of interest was ‘B’. The HDR flanker effect was equivalent to an 18.0 % change in the target contrast mixture (p < 0.01), based on the psychometric curves’ threshold crossings at 50 %-choose-A. Error bars show 5 to 95 % confidence intervals based on Psignifit and 400 trials. The effect is weaker but significant (p < 0.05) for 40 cd/m² (10 × darkening) adapting blank screen (B) and is abolished when there is no luminance change (C, 4 cd/m²).

Declaration of Competing Interest
None.

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Kleiner, M. (2017). Personal communication with Mario Kleiner, Psychtoolbox software support. Newer generation cards (e.g. the AMD Volcanic Islands series) are currently software limited to at most 11 bpc due to the current graphics driver design. A special xorg.conf setup is needed to enable this experimental mode, as described in the “help PsychImaging” section for “EnableNative64bitFramebufer”, and it only works on some desktop environments, e.g. GNOME-3 and maybe Ubuntu’s standard Unity interface. Also, according to https://www.x.org/wiki/RadeonFeature, examples of such AMD cards of the “Sea Islands” (CIK) generation are the models HD7790, R7 260, R9 290, and R9 M280X. These are marketing names which map to true hardware in very often confusing ways, so it is better to double-check. Such cards are also known under their internal GPU core code names BONARE, KABINI, MULLINS, KAVERI, HAWAII, or as cards of the “GraphicsCoreNext 1.1” (GCN 1.1) or ‘2nd generation graphics core next’ generation. According to https://en.wikipedia.org/wiki/Graphics_Core, the Radeon HD 8770 may work as well. After updating to the latest Psychtoolbox and running PsychLinuxCon, the Radeon’s extended debug output to make sure the projector is truly deected as 12 bpc capable, because even expensive display devices can have buggy EDID information which misrepresents their color resolution. One way to check this is to open a terminal and type “sudo su”, “echo 1 & /sys/module/drm/parameters/deep_color”, and it only works on
debug”, unplug/replug the projector to trigger the display redetection, “cat /var/log/syslog | grep bpc” (should report “… Display bpc=12, returned bpc=12” and “Assigning HDMI sink color depth as 12 bpc), and “echo 0 & /sys/module/drm/parameters/debug).

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