PRISM: Separating the Pupillary Light Reflex from Reward Anticipation in a Luminance-Controlled Infrared VR Headset

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Abstract

Anhedonia, the loss of the ability to anticipate or experience pleasure, affects about 70% of people with major depressive disorder and predicts poor remission, yet it is still tracked by recall-biased interviews and questionnaires. Pupil dilation during reward anticipation is a candidate objective marker because it tracks locus coeruleus norepinephrine output, but the cognitive signal is roughly an order of magnitude smaller than the pupillary light reflex, so any cue that changes screen brightness contaminates the measurement. We built a low-cost VR headset with off-axis 850 nm infrared illumination and dual eye cameras, and a browser-based monetary incentive delay task whose five cues are matched in integrated luminance within 1% and enforced by a continuous-integration check. Across 127 cue-locked trials the pupil response was real (outside all 2000 random-onset null draws, $p < 5\times10^{-4}$) but identical across win, loss and neutral cues, and the late cognitive window correlated r = 0.78 with the early reflex window. Subtracting a single scaled reflex template, fitted on value-free sessions, cut trial-level dispersion 2.7 to 4.2x and left no incentive effect (p = 0.48). The result is an acquisition and analysis pipeline that detects the light-reflex confound and separates it from the cognitive response.

Background

Anhedonia is common and poorly measured

About 70% of patients with MDD report anhedonia and it predicts non-remission [1]. Current tools (interview, SHAPS, DARS) are self-report, recall-biased, and agree only weakly with each other [2], so response is judged over months.

Pupil dilation tracks norepinephrine

Locus coeruleus firing precedes non-luminance pupil change spike for spike [3]. Blunted anticipatory dilation in the monetary incentive delay (MID) task scales with symptom load and anhedonia in MDD [4, 5].

The light reflex is larger than the signal

The pupillary light reflex is about 10x larger than cognitive dilation, and published incentive effects are only 0.2 to 1% of baseline. If two cues differ in brightness, a cue-locked difference can come from the light they emit rather than their value [6].

Method

Headset hardware (Fig. 1)

Printed goggle shell with a phone slot for the stimulus display, 850 nm IR LEDs mounted off-axis so the pupil images dark against a bright iris, and 60 fps USB IR eye cameras. Corneal irradiance is 1.2 W/m² at 28 mm, 80× under the IEC 62471 limit. Built from commodity parts (Teensy 4.1, OV9281 UVC, 850 nm LEDs).

Luminance-controlled MID task (Fig. 2)

One of five cues (win +200 or +50, loss −100 or −25, neutral 0) appears for 500 ms, then a 6 to 7 s anticipation cross, an adaptive 120 to 600 ms target held at a 66% hit rate, then 2 s feedback. Cue colour × lit area is equated to 1% (sRGB / BT.709) and re-verified on every commit.

Acquisition and analysis

Frames carry one monotonic clock and a Teensy 4.1 photodiode box marks true target onset. Pupils are segmented by threshold-ellipse fitting, blinks rejected on velocity and level, traces baselined to the 500 ms pre-cue median. Significance uses a random-onset null (n = 2000).

Requirement	Target	Achieved
Pupil resolution	20 to 30 px	25 to 45 px
Cue luminance match	≤ 2%	1.0%
Session length	≤ 5 min	5.3 min
Cost of materials	< $1200	not yet costed
Valid pupil frames	≥ 80%	≥ 99.7%

Table 1: *Need specifications and what the built system delivers. Session length is the 20-trial recorded block.*

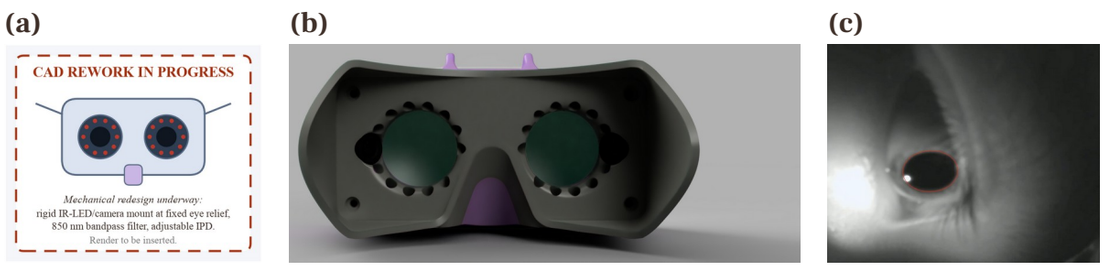


Figure 1: *Headset. (a) Mechanical redesign in progress, render to be inserted; (b) current build, eye side, with off-axis 850 nm IR LED rings around each camera port; (c) IR frame with fitted pupil ellipse (red), dark-pupil imaging.*

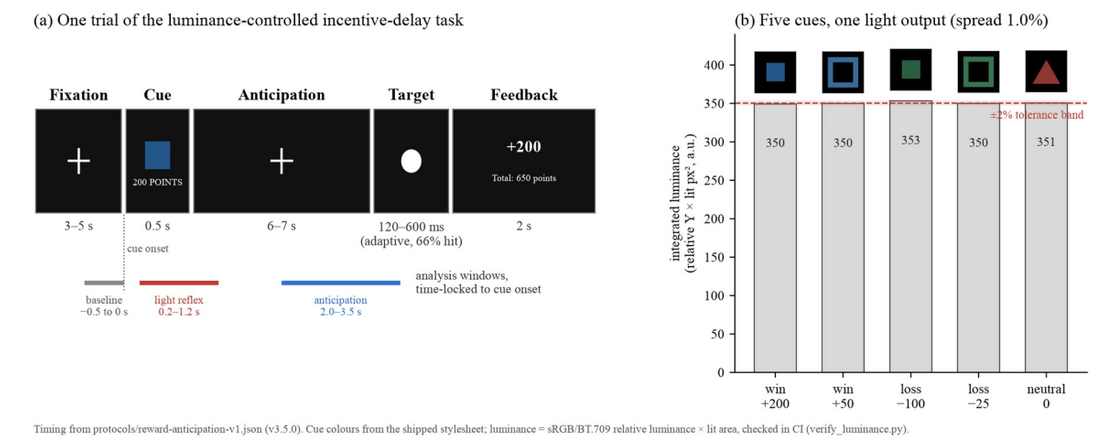


Figure 2: *Luminance-controlled incentive-delay trial and the five cues. Every cue emits the same integrated light (spread 1.0%, tolerance 2%), so a pupil difference between cues cannot come from screen brightness.*

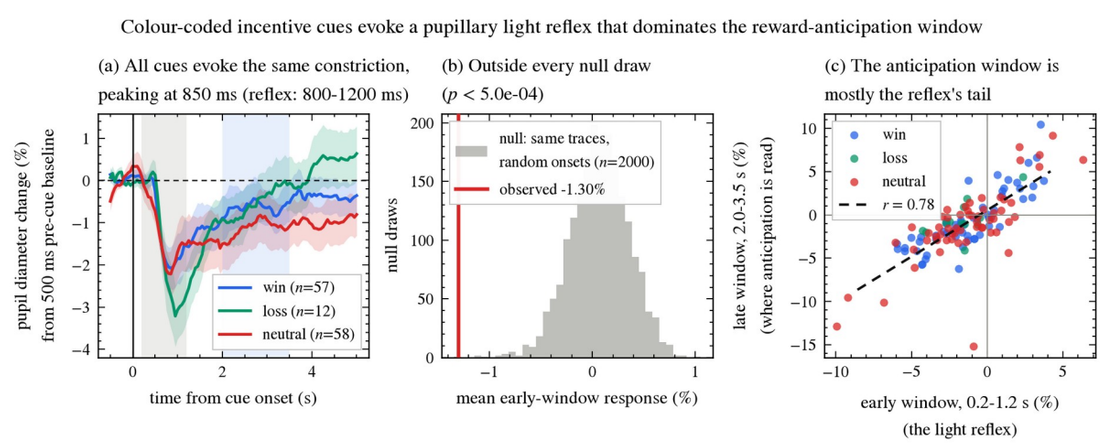


Figure 3: *The cue-locked response is real, but it is the light reflex. (a) All three cue types constrict identically, peaking at 850 ms; (b) the early-window response lies outside all 2000 random-onset null draws; (c) the late anticipation window tracks the early reflex window trial by trial (r = 0.78).*

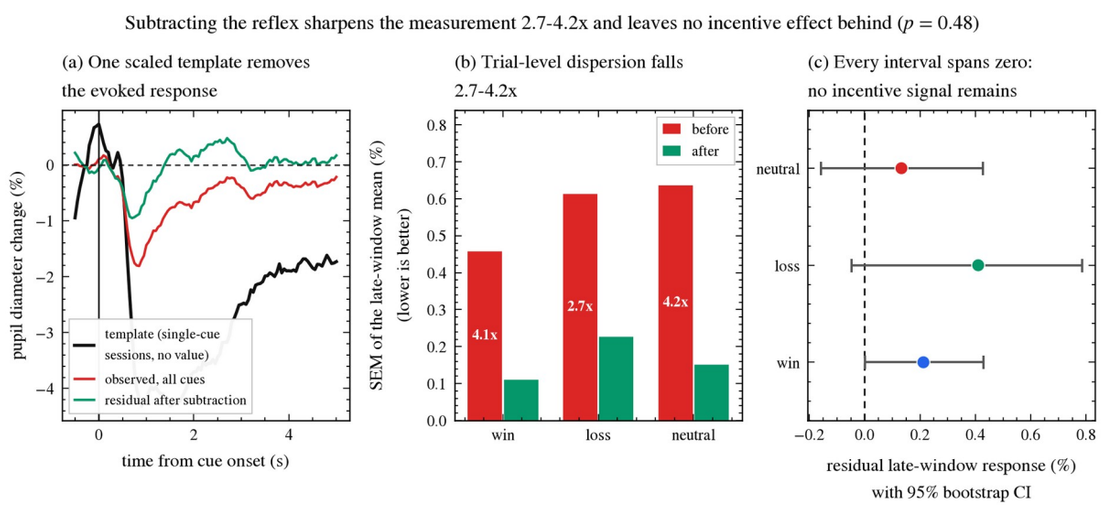


Figure 4: *Template subtraction removes the reflex. (a) A single scaled template from value-free single-cue sessions matches the evoked shape; (b) late-window SEM falls by 2.7 to 4.2x per cue; (c) residual incentive effects all span zero (95% bootstrap CI), p = 0.48.*

Results

Detection. Across 127 trials from 3 participants, detection was valid on ≥ 99.7% of frames per eye and the cue-locked constriction (−1.30% over 0.2 to 1.2 s) fell outside all 2000 random-onset null draws ($p < 5\times10^{-4}$; Fig. 3b).

Confound. All three cue types produced the same constriction (Fig. 3a). No incentive effect survived in any measure, and the direction flipped between participants. The late window correlated at r = +0.78 with the early reflex (Fig. 3c), so it was largely the tail of that reflex.

Correction. One scaled template, fitted on single-cue sessions with no assigned value, removed the evoked shape (Fig. 4a), cut trial-level SEM by 2.7 to 4.2x, and left residual effects whose intervals all include zero (Fig. 4c, Table 2).

Cue	n	SEM before → after (%)	Gain	Residual effect
win	57	0.46 → 0.11	4.1×	CI spans zero
loss	12	0.61 → 0.23	2.7×	CI spans zero
neutral	58	0.63 → 0.15	4.2×	CI spans zero

Table 2: *Per-cue summary of the template correction (Fig. 4b, 4c). Subtracting the reflex sharpens the late-window measurement by 2.7 to 4.2x, and every residual incentive effect still spans zero (omnibus p = 0.48).*

Discussion

We measured a cue-locked pupil response with high confidence, then showed that the response carried no information about reward value. Without luminance-matched cues and a random-onset null, the same data would have been read as a 1.3% anticipatory effect.

Any colour-coded MID task on any display produces this reflex, so the problem is not specific to our hardware. The 2.0 to 3.5 s window that most studies analyse sits on the recovery tail of that reflex (Fig. 3a), and in our data the two windows correlate at r = +0.78.

Template subtraction is cheap and needs no model of the reflex. The template is fit on sessions where no cue carried a value, so it cannot absorb a real incentive effect and can only remove what every cue has in common. The resulting 2.7 to 4.2x drop in trial-level dispersion is what a study this size needs to reach usable power.

Limitations

Pilot data are from three healthy adults with 12 to 58 trials per cue, in pixel units without mm calibration, and trial timing was reconstructed from screen video rather than a logged event stream. Blue win cues remain a wavelength confound, because melanopsin drives a sustained response that photopic matching does not remove. None of this tests anhedonia. It tests whether the measurement can support that question later.

Conclusion

We built a low-cost infrared VR headset and a luminance-verified incentive task, then used them to show that the dominant cue-locked pupil signal in a colour-coded MID task is the light reflex rather than reward anticipation. One scaled template removes it and sharpens the measurement 2.7 to 4.2x.

PRISM provides the hardware, the stimulus check that runs in CI, and the analysis needed to separate the reflex from the cognitive response.

Next steps

- Counterbalance the cue-to-value mapping across participants, carry value by shape instead of colour, and hold the label key until analysis is locked.
- Confirm equiluminance at the eye with a photometer and calibrate diameter to mm.
- Run a powered study of at least 40 trials per cue with DARS-scored participants, adding dilation slope as a secondary outcome.

Acknowledgments

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References

1. Wu C, et al. The characteristics of anhedonia in depression: a clinically oriented review. Transl Psychiatry. 2025.
2. Silvia PJ, et al. Self-report measures of anhedonia weakly correspond to clinical interviews. Pers Individ Dif. 2021.
3. Joshi S, Li Y, Kalwani RM, Gold JI. Relationships between pupil diameter and neuronal activity in the locus coeruleus. Neuron. 2016.
4. Schneider M, et al. Pupil dilation during reward anticipation is correlated to depressive symptom load in MDD. Brain Sci. 2020.
5. Brendler A, et al. Assessing hypo-arousal during reward anticipation with pupillometry in MDD: replication. Sci Rep. 2024.
6. Mathôt S, Vilotijević A. Methods in cognitive pupillometry: design, preprocessing, and statistical analysis. Behav Res Methods. 2022.
7. DelDonno SR, et al. The titrated monetary incentive delay task. J Clin Exp Neuropsychol. 2019.