



# Real objects maintain superior size-distance scaling to afterimages under sudden and adapted darkness conditions<sup>☆</sup>

Amy Siobhan Millard<sup>a</sup>, Irene Sperandio<sup>b</sup>, Philippe A. Chouinard<sup>a,\*</sup> 

<sup>a</sup> Department of Psychology, Counselling, and Therapy, La Trobe University, Australia

<sup>b</sup> Department of Psychology and Cognitive Science, University of Trento, Italy

## ARTICLE INFO

### Keywords:

Size constancy  
Distance perception  
Afterimages  
Dark adaptation  
Specific distance tendency  
Low-light environments  
Visual perception

## ABSTRACT

Human vision must adapt to varying lighting conditions, particularly in low-light environments where depth perception and size constancy are challenged. This study examined size-distance scaling for real objects and afterimages under sudden and adapted darkness conditions. Real objects exhibited more stable scaling than afterimages, closely aligning with Emmert's law, while afterimages showed substantial deviations. Although dark adaptation modestly improved size-distance scaling for both stimulus types, it did not fully restore veridical perception. Contrary to expectations, afterimages did not benefit more from adaptation than real objects, suggesting that their reliance on external depth cues exceeds what mesopic adaptation alone can compensate for. Additionally, perceived brightness influenced distance misperceptions, with brighter stimuli associated with greater errors—particularly for real objects. These findings highlight the limitations of internally generated stimuli in maintaining perceptual stability in darkness and emphasise the critical role of environmental and stimulus-based depth cues in supporting size constancy.

## 1. Introduction

The human visual system functions optimally in well-lit environments, where multiple depth cues are available to support stable object perception. However, natural viewing conditions are often dynamic and unpredictable, requiring adaptation to fluctuating lighting and reduced visual information. While gradual reductions in illumination (e.g., dusk) allow for progressive visual adjustments, sudden darkness (e.g., power outages, tunnels, abrupt loss of streetlights while driving) induces a more abrupt transition, placing demands on visual perception. A key function of the visual system in these conditions is size constancy: the ability to perceive an object as maintaining a consistent size despite changes in viewing distance (Andrews, 1964; Gregory, 1973; Morgan, 1992). Size constancy is thought to be achieved through the integration of retinal image size, depth cues, and cognitive factors (see Sperandio & Chouinard, 2015 for review).

Many studies use darkness paradigms to examine size constancy, yet little research has explicitly examined how partial adaptation to darkness affects depth and size perception. Most real-world low-light conditions involve mesopic vision, where both rods and cones remain

active, rather than full scotopic adaptation (Barbur & Stockman, 2010). Even without complete rod-based adaptation, short adaptation periods improve visual sensitivity (Kalloniatis & Luu, 1995), enhancing the detection of low-contrast features such as faint edges and luminance variations. Since size constancy relies on depth cues, even small gains in sensitivity could help preserve spatial perception in darkness by enabling the detection of low-contrast pictorial cues that may still be present in low lighting. Furthermore, objects inherently carry depth information, meaning that even in very dim conditions, their shading, contrast edges, or luminance properties may still be usable for depth scaling. Extracting distance information from such cues in the dark is common in everyday scenarios. For example, when driving at night, the taillights of a leading vehicle provide critical data about traveling distance and speed, even in low-visibility conditions.

Our previous work directly compared perceptually equivalent real objects and afterimages under a variety of visual environments, including binocular viewing in typical lighting and in abrupt, complete darkness (Millard et al., 2025). Unlike real objects or real images that physically exist in the environment, afterimages are internally generated stimuli. Fixed to the retina, they are projected onto surfaces in the

<sup>☆</sup> This article is part of a special issue entitled: 'Visual Aftereffects' published in Vision Research.

\* Corresponding author at: George Singer Building, La Trobe University, Room 460, Bundoora Campus, Melbourne, Victoria 3086, Australia.

E-mail addresses: [a.millard@latrobe.edu.au](mailto:a.millard@latrobe.edu.au) (A.S. Millard), [irene.sperandio@unitn.it](mailto:irene.sperandio@unitn.it) (I. Sperandio), [p.chouinard@latrobe.edu.au](mailto:p.chouinard@latrobe.edu.au) (P.A. Chouinard).

surrounding environment and scale in size with the apparent distance of that surface (Emmert, 1881). In that experiment, afterimages were found to be more error-prone than real objects in reduced visual environments, but especially in sudden darkness. Specifically, size judgments for afterimages deviated more strongly from Emmert's law — the principle that perceived size scales with the perceived distance of the surface onto which a fixed retinal image is projected (Emmert, 1881). Because afterimages are retinal projections that must be 'pinned' to surfaces in the environment, their size-distance scaling hinges on environmentally derived binocular and monocular depth signals (e.g., binocular disparity, vergence, pictorial cues), whereas physically present objects are already anchored in the scene and therefore retain more accurate scaling when those environmental signals are weakened in low lighting. However, it remains unclear whether dark adaptation (i.e., the process by which the visual system increases its sensitivity in low-light conditions) mitigates these perceptual errors, particularly for afterimages, which lack the intrinsic depth structure of real objects.

Notably, Millard et al. (2025) used a sudden darkness condition where the participant had both eyes open, so the robust size-distance scaling we observed for real objects in darkness likely benefitted from the broader cue set available under such circumstances (e.g., binocular disparity, more accurately calibrated vergence, and duplicate pictorial information). When those cues are progressively stripped away (e.g., by occluding one eye or, more severely, by forcing monocular pinhole viewing that also suppresses accommodation), perceived size drifts toward retinal image size (Chalmers, 1952). Importantly, ordinary monocular viewing still retains appreciable constancy for real objects — our own data show only a modest drop in accuracy relative to binocular viewing.

However, extreme cue-reduction paradigms used in many classic size constancy studies reveal the limits of size-distance scaling for real objects (e.g., Hastorf & Way, 1952; Holway & Boring, 1941; Ittelson, 1951; Kilpatrick & Ittelson, 1953; Lichten & Lurie, 1950). While valuable for understanding how size constancy breaks down in extreme cue-reduced conditions, such artificial viewing constraints do not reflect natural low-light vision, where both eyes typically remain available. Further, these studies often assume that vision remains stable once darkness is introduced but fail to account for the fact that sensitivity to depth cues may gradually improve as adaptation progresses. This raises the possibility that prior reports of size constancy breakdowns in darkness may partially reflect a lack of adaptation rather than a true absence of size scaling mechanisms.

Additionally, while some studies have explicitly mentioned adaptation periods ranging from 3 to 10 min (e.g., Chalmers, 1953; Over, 1960; Predebon, 1992), most do not detail how exposure to darkness was managed or report the exact luminance of testing environments and stimuli. These omissions make it difficult to determine whether findings reflect sudden sensory deprivation or a gradual transition to low-light vision. Explorations with size-distance scaling of afterimages in the dark also share this issue (e.g., Gregory et al., 1959; Mon-Williams et al., 1997; Weintraub & Gardner, 1970). This lack of methodological clarity presents a key limitation in the literature, as adaptation occurring during experimentation may influence results, making it difficult to disentangle immediate darkness effects from gradual improvements in visual sensitivity.

Furthermore, few studies account for whether vision was mesopic or scotopic, despite these being fundamentally different perceptual states. Scotopic vision is fully rod-based, leading to grayscale perception and reduced ability to detect fine details. In contrast, mesopic vision involves both rods and cones, allowing a greater degree of colour and depth perception and dominates most real-world nighttime settings. These shifts reflect the gradual change in retinal processing, where cone-driven vision gives way to rod dominance as luminance decreases (see Hecht et al., 1937). Since dark adaptation can shift visual processing between these states, failing to account for how long participants have been in darkness or the luminance levels of the space may introduce variability

into the size constancy literature. Because scotopic vision lacks colour perception, reliable colour discrimination during tasks can serve as a functional indicator that participants remained in the mesopic range. By explicitly controlling for mesopic adaptation in a structured within-subjects design, the present study addresses this gap by systematically testing how size-distance scaling is affected by sudden versus adapted darkness, reflecting functional low-light vision in everyday contexts.

Notably, recent research suggests that even subtle cues can restore size constancy in darkness. For example, linear perspective (Norman et al., 2022), vergence eye movements (Sperandio et al., 2013), and proprioceptive feedback (Chen et al., 2018; Sperandio et al., 2013) have each been shown to restore size constancy in darkness by compensating for the absence of typical depth cues in reduced-visibility environments. However, other manipulations, such as conceptual knowledge of the object's distance (Wang et al., 2024) appear to be insufficient to restore size-distance scaling — possibly because they operate at a conceptual level rather than altering the sensory input itself. Given this pattern, it remains unknown whether dark adaptation, as a basic sensory adjustment akin to changes in vergence or contrast detection, might similarly improve size constancy in darkness. Since no studies have directly tested whether adaptation alone is enough to improve size constancy, this study provides the first systematic evaluation of whether visual sensitivity gains from mesopic adaptation are sufficient to restore perceptual scaling.

The present study builds on prior findings by systematically testing whether dark adaptation alone is sufficient to improve size-distance scaling in low-light conditions. Given that small adjustments to cue availability have been shown to restore size constancy in darkness, dark adaptation may similarly facilitate the use of depth cues that remain partially available in low-light environments (immediately reduced) and adapted darkness (where participants have time to adjust), testing whether even brief adaptation enhances size-distance scaling and whether this effect differs for real objects and afterimages. Participants were asked to make perceptual judgements of the size and distance of the stimuli to examine size-distance scaling. Perceptual judgments of the colour properties of the stimuli were also collected to (1) confirm that vision remained in the mesopic range and (2) ensure that real objects and afterimages remained perceptually comparable. It was hypothesised that both stimuli would be perceived more accurately in the adapted dark condition, as increased visual sensitivity may allow for better utilization of residual contrast-based depth cues. Furthermore, afterimages were expected to benefit more from dark adaptation than real stimuli, as their positioning within the visual field relies more heavily on binocular and monocular depth cues, making them more vulnerable to misperception in sudden darkness.

## 2. Method

### 2.1. Participants

A power analysis was conducted prior to the study using G\*Power 3.1 to determine the required sample size. Based on previous findings (Millard et al., 2020), which reported an average  $\eta_p^2 = 0.46$  and Cohen's  $d = 1.07$ , a large effect size (Cohen's  $f = 0.40$ ) was assumed. The analysis, set at 95 % power and an alpha level of 0.05, indicated that a sample of 15 participants would be adequate for a two-way repeated-measures ANOVA. To account for potential variability in the newly introduced experimental conditions, 20 participants were recruited for the study (6 males, 14 females; age ranged from 19 – 38 years,  $M = 26.05$ ,  $SD = 5.41$ ).

Participants were screened to ensure they had normal or corrected-to-normal vision and were required to be right-handed. All assessments were conducted with participants using their normal visual correction, where applicable. Accommodation and vergence were assessed using the Royal Air Force Near Point Rule (Neely, 1956) which measures the closest point at which a person can focus before blurring

occurs (near point of accommodation) and the closest point at which single, binocular vision is maintained before experiencing diplopia (double vision; near point of convergence). A score of  $\leq 5$  cm represents the best possible performance, indicating that these abilities were maintained to the nose. The near point of binocular accommodation ranged from  $\leq 5$  cm to 12 cm ( $M = 7.95$ ,  $SD = 2.78$ ), indicating excellent to normal accommodation. The near point of convergence ranged from  $\leq 5$  cm to 10 cm ( $M = 6.90$ ,  $SD = 2.25$ ), reflecting strong to normal vergence ability, with no cases of convergence insufficiency detected.

Additional screening included assessments of visual acuity (Snellen chart; Snellen, 1862), stereoacuity (Vision Assessment Corporation, n.d.), and colour vision (Ishihara's Test for Colour Deficiency; Ishihara, 1918). Binocular visual acuity ranged from 20/13 to 20/30, stereoacuity scores were within normal limits with thresholds of 16 s of arc or better ( $M = 12.85$ ,  $SD = 1.08$ ), and no participants exhibited colour vision deficiencies. Ethical approval was granted by the Human Research Ethics Committee of La Trobe University. Informed consent was obtained from all participants, who were compensated with gift vouchers for their time and participation.

## 2.2. Procedure

### 2.2.1. General overview

On each trial, participants viewed a ring-shaped stimulus at one of 10 distances in a darkened room. The ring was either physically displayed on a screen (a real image) or projected onto the screen as a negative afterimage (following exposure to an inducing light). After viewing the stimulus, participants first estimated how far away it appeared. Then, using an on-screen matching tool, they adjusted a new comparison ring's size and colour to match their perceptual experience of the stimulus ring they had just seen. The real image and afterimage stimuli were designed to appear as perceptually similar as possible (see Millard et al., 2025 for detailed evaluation of the comparability of these stimuli). The setup also ensured that all stimuli appeared the same size on the retina regardless of distance. Thus, any variation in perceived size should reflect how the viewing context was interpreted by the visual system. By comparing participant matches across distances and conditions, we measured how well perceived size scaled based on available depth information from the stimuli and the environment.

This study employed a two (Stimulus Type: real image, afterimage)  $\times$  two (Dark Environment: sudden darkness, adapted darkness) repeated-measures design. Binocular viewing was used across all conditions to better approximate size constancy mechanisms in naturalistic dark environments, rather than employing artificial depth cue

restrictions such as monocular viewing through a pinhole to eliminate oculomotor cues. The real image and afterimage stimuli were presented at distances ranging from approximately 2 m – 6 m from the observer. One stimulus was presented at each of the 10 distances in each type of darkness, so every participant completed 40 trials in total (20 trials per combination of stimulus type and darkness condition). A Latin squares design was implemented to counterbalance the order of stimulus type and dark environment across participants, ensuring balanced exposure to all conditions. The experimental setup, stimulus presentation, and task procedures were kept as identical as possible across all trials, with the only variation being the stimulus type.

### 2.2.2. Testing space and stimuli

The study took place in an 8 m  $\times$  4 m room. The setup comprised a testing station with two computers, associated peripherals, and a chinrest. From the centre of this station extended a blocking screen positioned 53.52 cm from participants' eyes (when in the chinrest) and, on a sliding track, a 55-inch organic light emitting diode (OLED) display (see Fig. 1). When raised, the blocking screen completely obscured the view of the OLED screen in the testing space. It could be instantly lowered into a nesting box using a lever to reveal the scene to the participant when needed in a trial. The OLED screen could be rapidly moved on the sliding track to one of ten preset distances, each 44 cm apart, ranging from 196.20 cm from the observer (nearest) to 590.67 cm (farthest), representing a near-to-intermediate space within the typical human interaction range for objects in the environment. Participants wore noise-cancelling headphones playing white noise so that sounds movement would not provide distance cues. OLED technology for the main screen was selected for its true-black capability: unlike conventional displays that emit a residual glow on black backgrounds, OLED pixels can switch off entirely, preventing stray light from affecting perception of afterimages or real objects in the dark conditions used in this study (see Millard et al., 2025 for further discussion of OLED use in this context). This was essential for maintaining darkness and for delivering high contrast and accurate colour for the stimuli and matching tasks presented on the screen.

Throughout, we use 'real object' or 'real image' when referring to the real stimuli to denote the externally presented 2D images rendered on the OLED display; it is 'real' here in contrast to an afterimage, which is internally generated and then projected onto the viewed surface. No separate 3D physical object was used. The real stimuli consisted of ten ring-shaped images (luminance 0.149 cd/m<sup>2</sup>) subtending a visual angle of 4.28 degrees, with physical sizes scaled to maintain a constant retinal size across all distances. The colour profile of these ring stimuli was a



**Fig. 1.** This figure is modified from Millard et al. (2025) and illustrates the experimental apparatus and testing setup. The images were taken under overhead lighting for visibility, but actual testing occurred in complete darkness. In the sudden darkness condition, the overhead lights were used between trials to prevent participants from adjusting to the dark. The surrounding walls near the participant were blocked out to minimise environmental cues. Panel A shows the participant-facing view, including the chinrest, Chronos response pad, keyboard, and mouse, with the blocking inducer screen in place and the OLED screen positioned at the furthest testing distance. Panel B provides a side view of the apparatus with the OLED screen placed at the nearest distance. Panel C displays the full length of the sliding track used to reposition the screen across testing distances.

dark blue (specifically, hue: 253°, saturation: 100 %, value: 10 %). This was chosen for being bright enough to be clearly visible against the black background of the OLED screen yet dim enough to not cast residual light glow against the surrounding walls, floor, and ceiling. Additionally, afterimages in this distinct colour profile could be recreated across individuals using a bright red inducer. For further discussion of the equivalency of these stimulus types, pilot testing of the stimuli and illumination of the room when stimuli were displayed, see also Millard et al. (2025). Afterimage stimuli were robust negative afterimages, induced using a red, ring-shaped light source on the blocking screen with a luminance of 7.41 cd/m<sup>2</sup>. This light ring was turned off during real image trials to ensure no afterimages were induced, but it provided a consistent central marker for participants to align their gaze. A fixation point, a small white dot, subtending a visual angle of 0.07 degrees (i.e., it was scaled to maintain a constant retinal size across distances), was present in the centre of the OLED screen in all trials. For reference, this visual angle corresponds to a small physical size of approximately 0.75 cm in diameter even at the furthest viewing distance.

### 2.2.3. Trials and the matching task

Each trial consisted of three phases: (1) fixation, (2) observation, and (3) matching. In the fixation phase (1), participants fixated on the central marker on the blocking screen for 10 s. In afterimage trials, this central marker was illuminated and induced the afterimage, whereas in real object trials, it was not illuminated and served only as a fixation marker, the same fixation period was used so that the order of operations was identical as possible across stimulus types. In the observation phase (2), after the 10 s countdown, the blocking screen was instantly lowered into the nesting box to reveal the OLED screen at one of the ten possible distances. The OLED screen would display a small white fixation dot in the centre of the screen, and surrounding it, either a real ring stimulus against a black background, or just the black background for an afterimage ring to be projected onto. Participants pressed a button on a response pad to indicate when they first became aware of the stimulus, provided a verbal estimate of its perceived distance, and pressed the button again when they completed their observation. For real images, this second button press denoted that the participant felt they would be able to recreate what they had seen in the matching tool. For afterimages, it denoted when the afterimage had faded and they could no longer observe it. Again, this protocol was mainly in place for capturing data on afterimage duration, but the order of operations was kept as identical as possible for the real image stimuli. In the matching phase (3), an on-screen matching tool appeared on the OLED showing a ring of a randomized size and colour profile. Participants freely adjusted these qualities until they believed it matched how the previously seen stimulus ring appeared to them. When the participant indicated they were satisfied with their match, the trial ended, triggering the PLATO spectacles to close and the blocking screen was raised to ready the testing space for the next trial. Because the same OLED screen served for both observation and matching *within* a trial, the two stimuli were always compared at the same physical depth; yet, across trials the screen itself was positioned at ten distinct viewing distances (2–6 m). Systematic changes in the matched size across those ten distances therefore provide a direct index of size-distance scaling under cue-reduced conditions.

Participants practiced using the matching tool in a familiarisation session before the experiment to ensure accuracy and efficiency. The tool was designed to have a user-friendly interface (i.e., substantial or finer adjustments to size could be quickly made with arrow keys, and participants were not required to have any knowledge of the different colour dimensions or adjust these inputs separately, as they could simply click from or adjust a colour picker until it ‘looked’ correct). Participants were explicitly instructed as follows during the familiarisation session: *“In this experiment, you will see a series of ring-shaped objects. Some will be real objects on the screen, and others will be afterimages you’ll project onto the screen, which we’ll create by having you look at the red light. For each ring, I’d like you to tell me how it appeared to you. First, you’ll estimate how*

*near or far away it looked. Then, you’ll adjust a new ring on the screen so that its size and colour match the one you just saw. Please base your answers only on your immediate visual impression – how big or small the ring looked, and how close or far away it appeared, whether it was bright or dark, or whether it appeared more pink, yellow, or another shade. Don’t answer based on what you think the ring ‘really’ was, or what it ‘should’ look like in the world. There are no right or wrong answers. Everyone’s perception is different, and since I can’t see what you see, the goal is for you to report your own perceptual experience as accurately as you can.”*

The matching task in this experiment required participants to recreate perceptual attributes of the target stimulus under the same conditions as initial stimulus presentation after a short delay. This approach was chosen to maximise correspondence between the data obtained and the actual perceptual experience, minimising the introduction of extraneous cues that might bias the match made by participants. We have found that this matching method, when paired with careful participant instruction that emphasises perception and large-scale physical changes to distance of the display screen, yields size constancy results consistent with traditional size matching psychophysics tasks (Millard et al., 2025).

### 2.2.4. Dark environments

Participants wore PLATO Visual Occlusion Spectacles (Translucent Technologies Inc.), which rapidly switch between transparent and translucent states. The lenses were opened during trials and closed when visual information needed to be restricted, providing an additional control layer alongside instructions to close eyes or room lighting manipulations. The testing space walls were painted matte black to further reduce unintended illumination throughout the experiment.

In the adapted darkness condition, participants were seated in complete darkness for five minutes before the start of each testing block (i.e., adapted afterimage trials and adapted real stimuli trials). During this period, the PLATO lenses were closed, participants were instructed to keep their eyes closed, and all room lighting was extinguished, with an average room luminance of 0.003 cd/m<sup>2</sup>. After the adaptation phase, testing commenced with the room lighting remaining off throughout the block, and participants were instructed to close their eyes between trials. The only light sources available were the OLED screen for stimulus presentation and matching tasks and the afterimage inducer when activated.

In the sudden darkness condition, participants were exposed to bright overhead lights (approximate room luminance of 400 cd/m<sup>2</sup> when turned on) immediately before each trial, with both the PLATO lenses and eyes open. Just before the trial began, while participants were seated with their head on the chinrest and facing the central ring on the blocking screen, the PLATO lenses closed to ensure uniform timing and exposure to visual information. Simultaneously, the room lights were extinguished, leaving the space in total darkness with an average luminance of 0.003 cd/m<sup>2</sup> for the trial’s duration. At the end of each trial, the bright overhead lights were reactivated while participants’ eyes and PLATO lenses remained open, preventing any build-up of dark adaptation. Since full scotopic adaptation can take over 30 min and mesopic adaptation typically begins within a few minutes (Hecht et al., 1937), this design ensured that participants remained in a photopic visual state during sudden darkness trials. As a result, vision during these trials reflected an abrupt loss of illumination without sufficient time for compensatory sensitivity gains.

## 2.3. Data preparation and analysis

From these procedures, seven dependent variables were obtained. Foremost, size constancy measures of the perceived size and distance of the stimuli. Secondary to these were the other perceptual qualities which captured a timing and colour profile of the stimuli. Specifically, the point at which participants became aware of the stimuli and the length time spent observing them, as well as the perceived hue,

saturation, and value (i.e., brightness) of the stimuli.

Size constancy measures were examined by determining the extent to which size and distance estimates deviated from Emmert's law (1881), with greater deviations from this theoretically perfect proportional relationship between size and distance indicating weaker constancy. Calculations were made as follows to create the real stimuli and predict what size the afterimage stimuli should appear as at each of the ten distances tested:

$$s = d \times \tan(\theta)$$

here, 's' denotes the object's perceived size, 'd' its perceived distance, and ' $\theta$ ' the visual angle it subtends on the retina. The principle holds that under optimal viewing conditions, if the visual angle is fixed, perceived size varies with viewing distance; conversely, if size is known, one can infer the perceived distance. Given this, there is a baseline for what size and distance the stimuli should be rated as by participants, at any of the distances tested, if their size-distance scaling mechanisms were intact. Thus, participant reports of the perceived size of the stimuli under darkness conditions were compared to the theoretically perfect predictions of size if viewing conditions were optimal, while perceived distance ratings were compared to the actual distances the stimuli were presented at.

This was done using a three-step regression procedure (see also Millard et al., 2020, 2025). First, a linear regression was fitted to each participant's size estimates across the tested distances to obtain the observed slope. Second, a separate regression was fitted to the theoretical values predicted by Emmert's law for the same distances. Third, the absolute difference between the observed and predicted slopes was computed. This difference quantified the deviation from perfect size-distance scaling. For interpretability, these deviations were converted into percentages (deviation/predicted slope  $\times$  100), where a value of 0 indicated perfect constancy (i.e., judgments changed in full proportion with distance, as Emmert's law predicts), while larger values indicated greater departures. 100 % (or greater) indicates a complete failure of size constancy. Further, while Emmert's law traditionally refers to perceived size, we also extended this approach to distance estimates by treating distance as the perceptual outcome and computing deviation from actual distance values in the same manner. As distance ratings were recorded as magnitude estimates, this data and the values for the actual distances used were standardised into z-scores before the regression slope calculations were performed.

Other perceptual attributes were analysed using additional measures. For the timing variables, we recorded the point of awareness as the time (in milliseconds) between the moment the blocking screen was lowered and the participant's first button press indicating stimulus detection. Observation time was defined as the interval between the first and second button presses, marking how long the participant continued to perceive the stimulus. Both measures were later converted into seconds for ease of interpretability. While these measures are often referred to as "onset" and "duration" in afterimage research, we adopted terminology that could be consistently applied across both stimulus types used in the study. Colour profile data were extracted directly from the HSV (Hue, Saturation, Value) outputs of the matching tool. In this colour model, hue corresponds to the type of colour and is measured in degrees around a 360° colour wheel (e.g., red at 0°, green at 120°, blue at 240°). Saturation reflects colour intensity, ranging from 0 % (completely desaturated, or grey) to 100 % (fully saturated). Value indicates brightness, also ranging from 0 % (black) to 100 % (maximum brightness). Together, these three parameters provide a multidimensional representation of participants' perceptual experience of colour.

An outlier analysis was conducted across all measures to ensure reliability and accuracy of participant responses. The dataset comprised seven measures (size, distance, point of awareness, observation time, hue, saturation, and value), two types of stimuli (real and afterimage), and two dark environments (adapted and sudden). Each participant (N

= 20) completed trials at ten different distances for each combination of stimulus type and dark environment, resulting in 40 trials per participant and a total of 800 trials. Consequently, we collected 5,600 data points. Outlier detection was performed by examining each data point within each measure (800 points per measure) for values that deviated more than three standard deviations from the mean. Data points exceeding this threshold ( $\pm 3$  standard deviations) were considered outliers and were subsequently removed from the analysis. This criterion led to the removal of 67 data points in total, representing 1.20 % of the entire dataset.

Statistical analyses were performed using JASP Version 0.18.3 (JASP Team, 2024) and GraphPad Prism version 6 (GraphPad Software, 2014). A two-way repeated measures analysis of variance (ANOVA) was conducted for each of the seven dependent variables at two levels for the first factor based on Stimulus type (i.e., real object and afterimage) and at two levels for the second factor based on Dark environment (i.e., adapted and sudden). When a significant interaction was observed, simple effects were examined using paired-sample *t*-tests, with Holm corrections applied for multiple comparisons where appropriate. Results were assessed at an alpha level of 0.05. All reported *p* values are based on two-tailed criteria and corrected for multiple comparisons. Effect sizes are reported as partial eta-squared ( $\eta_p^2$ ) for ANOVA results Cohen's *d* for pairwise comparisons. Bayesian ANOVAs were also conducted, integrating the conventional NHST framework with Bayesian analysis to provide a complementary probabilistic interpretation of the findings. Pearson's correlation coefficients (*r*) were computed to examine the relationships between size-distance scaling and age, visual acuity, stereoacuity, near point of vergence, near point of accommodation, observation time, and value. Observation time (i.e., duration) and value are indicators of afterimage strength, and equivalent measures for real objects were included to determine whether similar perceptual mechanisms influence both stimulus types. Effect sizes for the correlations were interpreted following Cohen's guidelines: *r* values of 0.10, 0.30, and 0.50 indicate small, medium, and large effects, respectively. Additionally, the coefficient of determination ( $R^2$ ) was calculated by squaring the *r* values, reflecting the percentage of variance in one variable explained by the variance in another.

In addition, using procedures outlined in previous work (see Millard et al., 2020, 2025), we performed two supplementary analyses to examine the more fine-grained differences in size-distance scaling across the different conditions. Briefly, the regression slopes for size perception in each testing condition are normalised and then subtracted from each other, in order of depth cue availability, to determine the relative contribution of the depth cues present in each environment. To determine at which distance the contribution of cues did not overlap (i.e., uniquely contributed), the regression slopes were also plotted to evaluate the mean perceived size with 95 % confidence intervals as a continuous function of distance for each environment (nearest distance being 196 cm, furthest 590 cm).

Additional analyses, following the approach of previous studies (Millard et al., 2020, 2025), examined more subtle variations in size-distance scaling across the dark viewing conditions. Regression slopes for size and distance judgments were normalised within each condition, and the difference between adapted darkness and sudden darkness was calculated to isolate the effect of dark adaptation relative to immediate exposure to dark visual scene without prior adjustment. This analysis evaluated how dark adaptation influenced the perception of size and distance scaling. Due to rounding, these values do not sum precisely to 100 %. To pinpoint specific distances where dark adaptation improved size-distance scaling accuracy, regression slopes were visualized by plotting the mean perceived size with 95 % confidence intervals as a continuous function of distance for each dark condition. Instances where confidence intervals did not overlap were identified as points of significant difference.

### 3. Results

#### 3.1. Overall summary

##### 3.1.1. Size constancy

Real objects were judged more accurately than afterimages for both size and distance, regardless of darkness condition. However, neither strictly adhered to Emmert's law as both were generally underestimated, with real objects deviating by 23 % for size and 34 % for distance, and afterimages deviating by 60 % and 67 %, respectively. Dark adaptation reduced size misperceptions compared to sudden darkness but had no effect on distance judgments. Across all distances, dark adaptation minimally influenced size scaling for real objects (~1.5 %) but accounted for nearly 10 % of the effect for afterimages. It contributed around 3 % to distance scaling for both stimuli and led to less variability in real object judgments. Size and distance judgments were not significantly correlated for either stimulus type, suggesting these perceptual processes are decoupled in darkness. However, distance judgments across stimulus types were related in adapted darkness, but not in sudden darkness. Additionally, stimuli perceived as brighter (higher in value) increased distance judgment errors.

##### 3.1.2. Other perceptual qualities

Real objects reached awareness 1.95 s faster than afterimages, and dark adaptation further reduced awareness time. Observation duration did not differ overall, but afterimages were observed longer in adapted darkness. No differences were found in hue or saturation, with both real objects and afterimages appearing highly saturated blue. Despite both stimulus types being rated as low in brightness (value), real objects appeared brighter, while afterimages were nearly black. Dark adaptation had no effect on colour perception.

#### 3.2. Size constancy.

##### 3.2.1. Size (% of deviation from Emmert's law)

ANOVA demonstrated a main effect of Stimulus type ( $F_{(1,19)} = 58.73$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.76$ ,  $BF_{10} > 1000$ ), a main effect of the Dark environment ( $F_{(1,19)} = 7.11$ ,  $p = 0.02$ ,  $\eta_p^2 = 0.76$ ,  $BF_{10} = 1.41$ ), and no interaction ( $F_{(1,19)} = 1.76$ ,  $p = 0.20$ ,  $\eta_p^2 = 0.08$ ,  $BF_{10} = 0.67$ ). See Fig. 2A.

As indicated by the main effects, the size of afterimages ( $M = 60.93$ ,  $SD = 21.42$ ) was judged 37.73 % less accurately than the size of real objects ( $M = 23.20$ ,  $SD = 13.61$ ). Dark adaptation also influenced size perception; when participants adjusted to the lighting, their size ratings were 5.42 % more accurate ( $M = 39.35$ ,  $SD = 25.78$ ) than when placed in sudden darkness ( $M = 44.77$ ,  $SD = 26.34$ ).

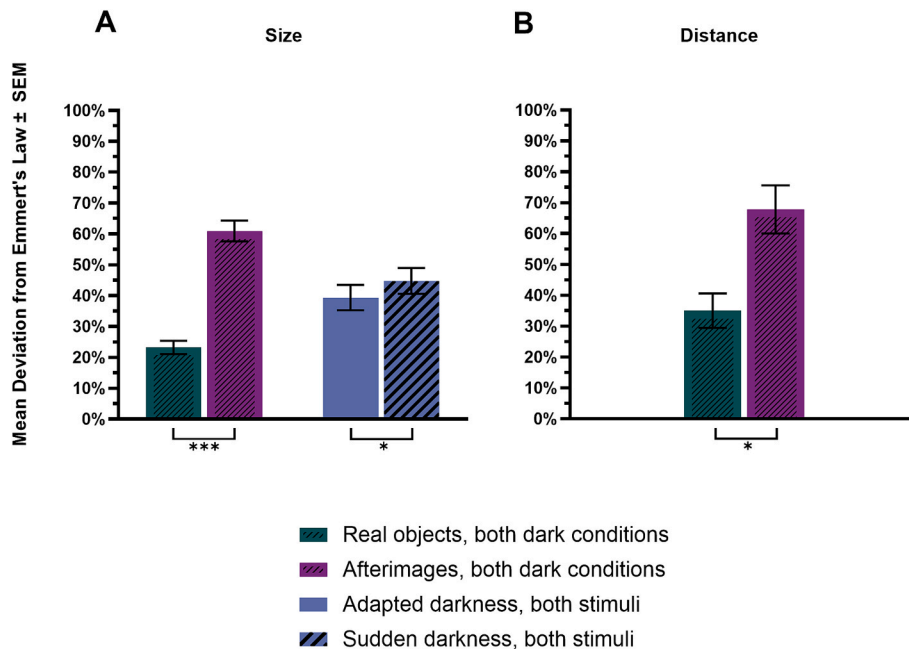
##### 3.2.2. Distance (% of deviation from Emmert's law)

ANOVA demonstrated a main effect of Stimulus type ( $F_{(1, 19)} = 12.53$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.38$ ,  $BF_{10} = 18.10$ ), no effect of the Dark environment ( $F_{(1, 19)} = 0.43$ ,  $p = 0.52$ ,  $\eta_p^2 = 0.02$ ,  $BF_{10} = 0.35$ ), and no interaction ( $F_{(1, 19)} = 0.07$ ,  $p = 0.78$ ,  $\eta_p^2 = 0.004$ ,  $BF_{10} = 0.29$ ). See Fig. 2B.

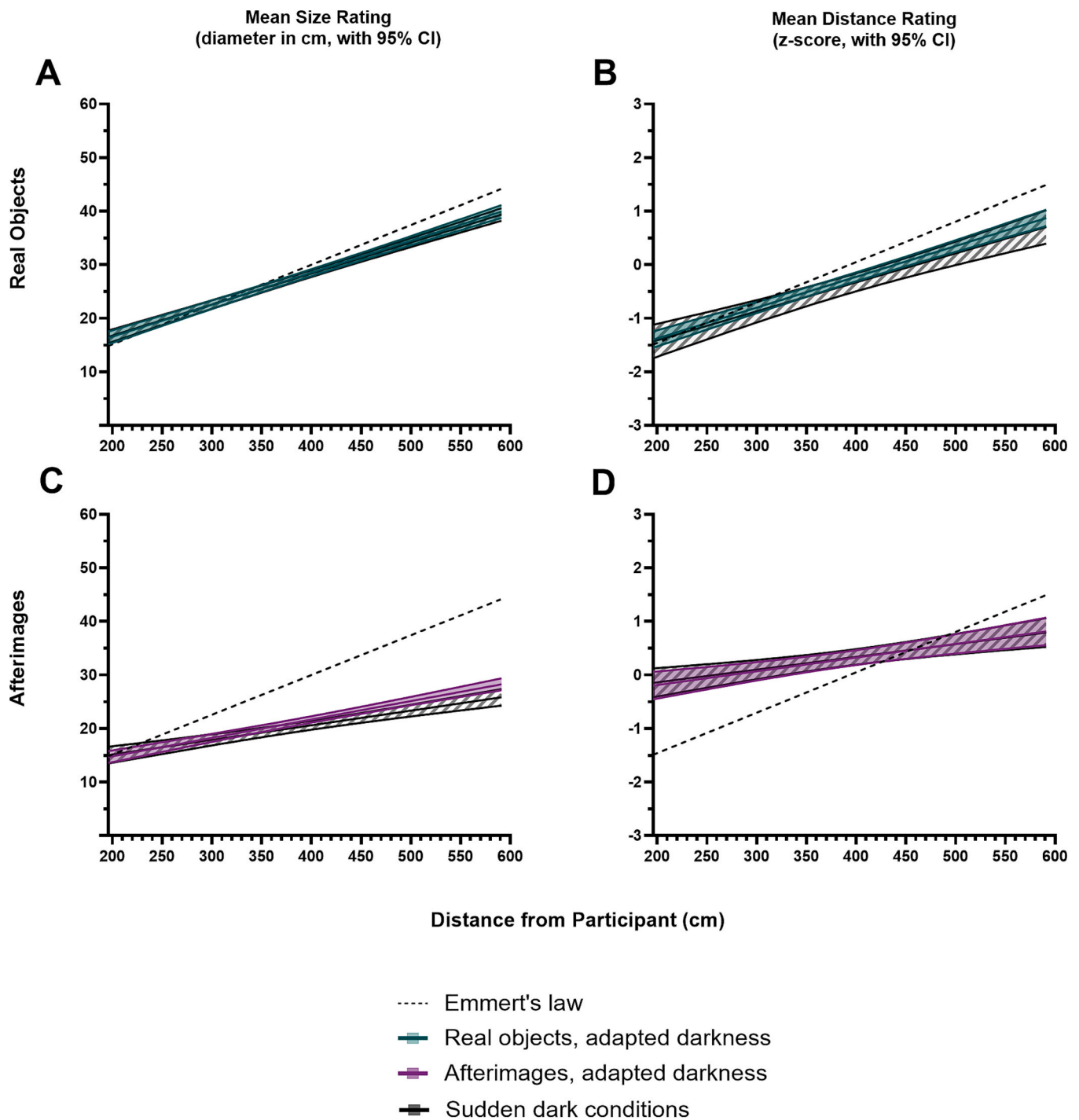
As indicated by the main effect of Stimulus type, the perceived distance of afterimages ( $M = 67.79$ ,  $SD = 49.38$ ) deviated 32.81 % more from Emmert's law than that of real objects ( $M = 34.98$ ,  $SD = 35.32$ ), showing reduced accuracy in distance judgments for afterimages.

##### 3.2.3. Relative impact of depth cues (mean with 95 % CI)

Based on the plotted regression slopes for size judgments of real objects (see Fig. 3A), sudden and adapted darkness conditions were similar across all distances, closely adhering to Emmert's law. Adapting to the dark contributed minimally to size scaling, with the majority of the effect driven by residual visual information available in darkness. At closer distances, slight over-constancy was observed, where objects appeared larger than their predicted size. Adapting to darkness contributed 1.56 % to size scaling, while other residual visual information accounted for 87.27 %, leaving 11.16 % unexplained.



**Fig. 2.** Means and standard error of measurement (SEM) for Size (2A) and Distance (2B; deviation from the theoretical slope calculated from Emmert's law); the x-axis corresponds to the matching testing conditions (in the legend in all graphs). Significance indicators below the x-axis show differences between stimuli type or dark conditions. \* $p < .05$ , \*\* $p < .01$ , \*\*\* $p < .001$ . The bars are colour-coded based on condition: teal for real objects and purple for afterimages. A thin line pattern in the centre indicates that both darkness conditions are represented in the data; a large line pattern for sudden darkness and no pattern for adapted darkness. The blue colour denotes that both stimulus types are represented in the data. Bars are grouped to reflect the structure of the main statistical effects (stimulus type and environment for size; stimulus type for distance).



**Fig. 3.** Mean and 95% confidence intervals for size (left column, diameter of ring in cm) and distance judgements (right column, magnitude estimations converted to z-scores) made in the two dark conditions from all participants, plotted as a function of distance. The plots are colour-coded based as follows: The dashed line represents the theoretically perfect slope of Emmert's law and is plotted identically across all four graphs as a frame of reference. The black striped underlay represents the data in sudden darkness across all four graphs. In 3A and 3B, the teal overlay represents the data for real objects in adapted darkness, similarly, 3C and 3D have a purple overlay for afterimage data in adapted darkness. In all graphs, the close overlap of the sudden dark and adapted dark lines reflect the similarity in participants' size or distance judgments under these conditions across most distances. It is interesting to note that less overlap occurs for afterimage size, not distance, and for real object distance, not size. Indicating that adapting to the dark did not provide universal improvements to accuracy, rather, it had a stimulus-specific and measure-specific effect.

For distance judgments of real objects (see Fig. 3B), sudden and adapted darkness conditions also followed Emmert's law across most distances. However, at farther distances, sudden darkness led to slightly greater deviations, with objects being misperceived as closer. Adapting to darkness contributed 2.93 % to distance scaling, other residual visual information accounted for 83.54 %, and 13.53 % was unexplained.

For size judgments of afterimages (see Fig. 3C), both sudden and adapted darkness conditions deviated significantly from Emmert's law, with more pronounced under-constancy at farther distances. Afterimages appeared consistently smaller than their predicted size, and the absence of contextual depth cues in sudden darkness exacerbated these errors. Adapting to the dark contributed 9.48 % to size scaling, while

other residual visual information accounted for 53.55 %, leaving 36.97 % unexplained.

For distance judgments of afterimages (see Fig. 3D), both conditions exhibited a flattened slope with significant deviations from Emmert’s law, reflecting reduced accuracy across all distances. The adapted darkness condition resulted in slightly better performance than sudden darkness, though both conditions showed large errors overall. Adapting to the dark contributed 2.79 % to distance scaling, other residual visual information accounted for 47.92 %, and 49.30 % was unexplained.

These findings indicate that adapting to the dark provides a modest stabilising effect on size and distance judgments for both real objects and afterimages, with a greater contribution to size scaling for afterimages than for real objects. Afterimages, being more error-prone and reliant on ambiguous internal signals, exhibited significantly larger deviations from Emmert’s law than real objects under both sudden and adapted darkness conditions. Real objects maintained greater perceptual stability, suggesting that their processing benefits from residual visual information even in darkness, while afterimages lack the robustness to integrate these cues effectively. This aligns with the broader observation that afterimages rely disproportionately on contextual information for perceptual stability, making them more vulnerable to disruptions caused by sudden lighting changes. Unlike real objects, afterimages are retinally anchored and tend to drift with eye movements, making them more difficult to stabilise and harder to judge accurately in dynamic or unfamiliar environments.

3.2.4. Correlations between size and distance (% of deviation from Emmert’s law)

Refer to Table 1. For real objects, size and distance judgments were not correlated in either adapted and sudden darkness, suggesting that the mechanisms driving size and distance scaling for real objects in darkness operate relatively independently, particularly when contextual information is reduced. The absence of a stronger relationship in either condition indicates that residual visual information in darkness may contribute differently to size and distance judgments.

For afterimages, size and distance judgments also showed non-significant correlations in either dark condition. This decoupling suggests that afterimages rely minimally on shared mechanisms for size and distance scaling and are inherently more variable under reduced visual conditions. The slightly higher correlation in adapted darkness may indicate some stabilization of perceptual scaling through dark adaptation, but this effect is limited compared to real objects.

For size judgments across stimulus types, no correlations were observed. This indicates minimal alignment in size judgments between

Table 1

Correlational relationships of size and distance between the variables, including r coefficients, p values, Cohen’s effect sizes, and R<sup>2</sup>.

Pearson correlation	r	p	Effect Size	R <sup>2</sup>
Between size and distance, for real objects				
Adapted to darkness	-0.04	0.87	small	0.00
Sudden darkness	-0.09	0.70	small	0.01
Between size and distance, for afterimages				
Adapted to darkness	0.15	0.49	small	0.02
Sudden darkness	-0.17	0.47	small	0.03
For size, between stimulus types				
Adapted to darkness	0.08	0.74	small	0.01
Sudden darkness	0.07	0.77	small	0.00
For distance, between stimulus types				
Adapted to darkness	0.57	<0.01**	large	0.32
Sudden darkness	0.37	0.09	medium	0.14

Note. Asterisks (\*) denote significance as follows: \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001 (two-tailed).

real objects and afterimages, regardless of the lighting condition. This finding is consistent with the observation that afterimages are more prone to perceptual errors, which likely disrupt any shared scaling mechanisms with real objects in reduced cue environments.

For distance judgments across stimulus types, a strong positive correlation was observed in adapted darkness, indicating that distance judgments for real objects and afterimages align more closely when participants are allowed to adapt to the dark. This suggests that dark adaptation enhances the integration of faint visual or non-visual cues that remain available under low-light conditions, leading to more consistent scaling strategies between the two stimulus types. In sudden darkness, a moderate correlation suggests that abrupt transitions may disrupt this alignment, particularly for afterimages, which exhibit greater variability in distance estimations.

These findings emphasize the differential effects of dark adaptation on the perceptual stability of real objects and afterimages. Real objects maintain greater independence between size and distance scaling in darkness, while afterimages display weak, inconsistent correlations, underscoring their greater susceptibility to perceptual errors. The stronger alignment between stimulus types for distance judgments in adapted darkness highlights the stabilizing role of adaptation in environments with limited visual cues. However, this alignment does not extend to size judgments, where afterimages remain more error-prone and decoupled from real objects under both conditions. This pattern underscores the inherent limitations of afterimages as internally generated stimuli in maintaining perceptual stability under reduced visual conditions.

Across all stimuli-dark environment conditions, the relationships between participant age, visual acuity, stereoacuity, near point of accommodation, near point of vergence, and observation time with deviations from Emmert’s law were non-significant. Age and other indicators of visual performance explained very little variance in size and distance misperceptions (r ranged from -0.39 to 0.43, p = 0.06 to 0.99, R<sup>2</sup> = 0.15 to 0.18), indicating that these factors did not systematically impact size-distance scaling. Similarly, observation time was not significantly correlated with deviations from Emmert’s law for either size or distance judgments (r = -0.17 to 0.06, p = 0.46 to 0.84, R<sup>2</sup> = 0.00 to 0.03), suggesting that shorter afterimage persistence or limited real object viewing durations did not impact judgment accuracy.

However, perceived value was significantly correlated with distance in two conditions, as shown in Table 2. In adapted darkness, afterimages with higher value exhibited a moderate relationship with greater deviations in judgements from the actual distances tested, suggesting that brighter afterimages impaired distance estimates when participants had

Table 2

Correlational relationships of value with size and distance across darkness conditions, including r coefficients, p values, Cohen’s effect sizes, and R<sup>2</sup>.

Pearson correlation	r	p	Effect size	R <sup>2</sup>
Between value and distance, for real objects				
Adapted to darkness	0.25	0.28	small	0.06
Sudden darkness	0.62	0.003**	large	0.38
Between value and distance, for afterimages				
Adapted to darkness	0.46	0.04*	medium	0.21
Sudden darkness	0.14	0.56	small	0.02
Between value and size, for real objects				
Adapted to darkness	0.13	0.58	small	0.02
Sudden darkness	0.06	0.80	small	0.00
Between value and size, for afterimages				
Adapted to darkness	0.34	0.14	medium	0.12
Sudden darkness	0.32	0.17	medium	0.10

Note. Asterisks (\*) denote significance as follows: \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001 (two-tailed).

adjusted to the dim environment. Value did not correlate with perceived size in either darkness condition or with perceived distance in sudden darkness. However, a similar pattern emerged for real objects, where higher value ratings were strongly associated with greater deviations from Emmert’s law in sudden darkness. This indicates that perceiving real stimuli as brighter also reduced distance judgment accuracy when participants were not given time to adapt to the lighting.

3.3. Other perceptual qualities

3.3.1. Point of awareness (s)

ANOVA demonstrated a main effect of Stimulus type ( $F_{(1, 19)} = 107.07, p < 0.001, \eta_p^2 = 0.85, BF_{10} > 1000$ ), a main effect of the Dark environment ( $F_{(1, 19)} = 4.76, p = 0.04, \eta_p^2 = 0.20, BF_{10} = 1.23$ ), and no interaction between the two factors ( $F_{(1, 19)} = 2.00, p = 0.17, \eta_p^2 = 0.10, BF_{10} = 0.19$ ). See Fig. 4A.

Real objects reached awareness more quickly ( $M = 1.89\text{ s}, SD = 0.53$ ) than afterimages did ( $M = 3.84\text{ s}, SD = 1.02$ ), with an average difference of 1.95 s. Dark adaptation also influenced time to awareness: participants became aware of stimuli slightly faster when adapted to the dark ( $M = 2.76\text{ s}, SD = 1.28$ ) compared to when placed in sudden darkness ( $M = 2.97\text{ s}, SD = 1.27$ ).

3.3.2. Observation time (s)

ANOVA demonstrated no main effect of Stimulus type ( $F_{(1, 19)} = 4.05, p = 0.06, \eta_p^2 = 0.18, BF_{10} = 1.64$ ), and no main effect of the Dark environment ( $F_{(1, 19)} = 1.41, p = 0.25, \eta_p^2 = 0.07, BF_{10} = 0.40$ ), but an interaction between the two ( $F_{(1, 19)} = 5.42, p = 0.03, \eta_p^2 = 0.22, BF_{10} = 4.20$ ). See Fig. 4B.

This interaction reflected a difference in how long participants observed afterimages versus real objects under different lighting conditions. Post hoc tests revealed that participants observed afterimages ( $M = 7.64\text{ s}, SD = 3.82$ ) for longer than real objects in the adapted dark condition ( $M = 5.31\text{ s}, SD = 3.42; t = -2.66, p = 0.02, d = -0.70, BF_{10} = 3.56$ ). No difference between stimulus types was observed in sudden

darkness ( $M = 6.44\text{ s}, SD = 2.75$  for afterimages vs.  $M = 5.69\text{ s}, SD = 3.18$  for real objects;  $t = -0.94, p = 0.23, d = -0.23, BF_{10} = 0.34$ ). When comparing each stimulus across dark conditions, observation time for real objects did not differ between adapted and sudden darkness ( $t = -1.09, p = 0.29, d = -0.12, BF_{10} = 0.39$ ), but afterimages were observed slightly longer in the adapted condition ( $t = 2.06, p = 0.05, d = 0.36, BF_{10} = 1.32$ ).

3.3.3. Hue (°)

ANOVA demonstrated no effect of Dark environment ( $F_{(1, 19)} = 0.02, p = 0.88, \eta_p^2 = 0.001, BF_{10} = 0.32$ ) or Stimulus type ( $F_{(1, 19)} = 0.30, p = 0.59, \eta_p^2 = 0.02, BF_{10} = 0.37$ ), and no interaction between the two factors ( $F_{(1, 19)} = 0.31, p = 0.59, \eta_p^2 = 0.02, BF_{10} = 0.34$ ). All means were between 238.70° and 239.97°, which corresponds to the 240° ‘blue’ band of colour in the 360° HSV colour space. See Fig. 5A.

3.3.4. Saturation (%)

ANOVA demonstrated no effect of Dark environment ( $F_{(1, 19)} = 0.10, p = 0.76, \eta_p^2 = 0.01, BF_{10} = 0.33$ ), or Stimulus type ( $F_{(1, 19)} = 0.02, p = 0.90, \eta_p^2 = 0.001, BF_{10} = 0.45$ ), and no interaction between the two factors ( $F_{(1, 19)} = 0.05, p = 0.83, \eta_p^2 = 0.002, BF_{10} = 0.31$ ). All means ranged between 87.57 % and 88.12 %, which represents very high purity of colour (i.e., little greyness) in HSV colour space. See Fig. 5B.

3.3.5. Value (%)

ANOVA demonstrated a main effect of Stimulus type ( $F_{(1, 19)} = 49.82, p < 0.001, \eta_p^2 = 0.72, BF_{10} > 1000$ ), and no effect of Dark environment ( $F_{(1, 19)} = 0.08, p = 0.78, \eta_p^2 = 0.004, BF_{10} = 0.31$ ) or interaction ( $F_{(1, 19)} = 0.65, p = 0.43, \eta_p^2 = 0.03, BF_{10} = 0.34$ ). See Fig. 5C.

Consistent with the main effect, real objects ( $M = 18.77, SD = 6.62$ ) were perceived as brighter than afterimages ( $M = 7.11, SD = 4.23$ ) on average. Although afterimages were physically presented against a 0 % OLED black background, participants nevertheless gave them non-zero ratings (range ~2–20 %), and estimates of the real images ranged between ~8–31 %, This indicates that ratings reflected subjective

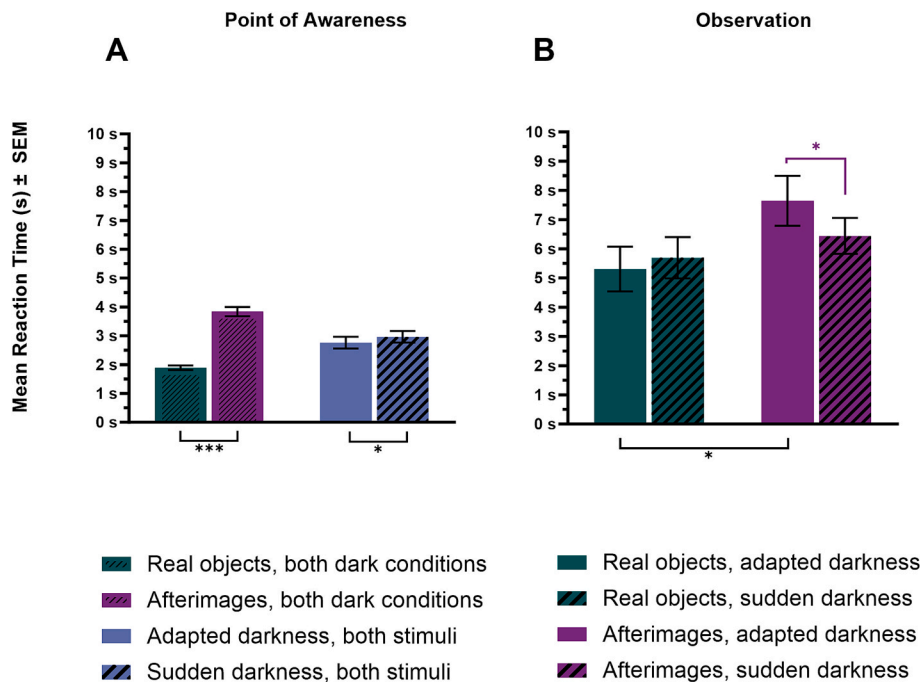
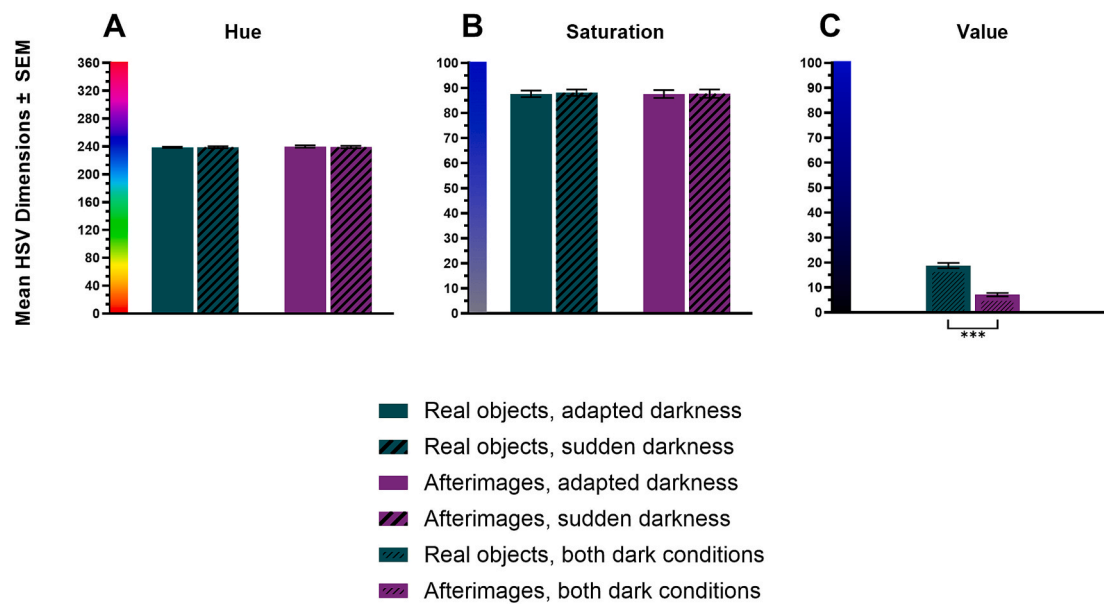


Fig. 4. Means and standard error of measurement (SEM) for Point of Awareness (4A) and Observation Time (4B; seconds); the x-axis corresponds to the matching testing conditions (in the legend in all graphs). Significance indicators below the x-axis show differences between stimuli type or dark conditions, significance indicators above the columns show differences within stimuli between dark conditions. \* $p < .05$ , \*\* $p < .01$ , \*\*\* $p < .001$ . The bars are colour-coded based on condition: teal for real objects and purple for afterimages. A thin line pattern in the centre indicates that both darkness conditions are represented in the data; a large line pattern for sudden darkness and no pattern for adapted darkness. The blue colour denotes that both stimulus types are represented in the data.



**Fig. 5.** Means and standard errors (SEM) for Hue (5A), Saturation (5B, and Value (5C); the x-axis corresponds to the matching testing conditions in the legend in all graphs. Significance indicators below the x-axis show differences between stimuli type. \* $p < .05$ , \*\* $p < .01$ , \*\*\* $p < .001$ . The bars are colour-coded based on condition: teal for real objects and purple for afterimages. A thin line pattern in the centre indicates that both darkness conditions are represented in the data; a large line pattern for sudden darkness and no pattern for adapted darkness.

experience rather than physical luminance levels of the screen display. Average value scores of 7 % to 18 % would all be considered ‘dark’ in HSV colour space, but afterimages appeared near black.

## 4. Discussion

### 4.1. Overview

The present study examined how dark adaptation influences size-distance scaling for real objects and afterimages under sudden and adapted darkness conditions. The results demonstrated that real objects were judged more accurately than afterimages in both conditions, consistent with previous research showing that real objects provide more robust depth cues, even under reduced viewing conditions (Millard et al., 2025). Further, dark adaptation led to small but significant improvements in size-distance scaling for both stimulus types, though it did not fully restore veridical perception. Contrary to our initial hypothesis, afterimages did not exhibit a unique benefit from adaptation, despite their greater reliance on external depth cues.

Additionally, results confirmed that participants remained in the mesopic vision range throughout testing, as evidenced by consistent colour perception and saturation values across conditions. This suggests that any improvements in size-distance scaling were not due to a shift to scotopic vision, but rather to enhanced contrast sensitivity during mesopic adaptation, when both rods and cones are active. While stimuli types remained perceptually comparable overall, afterimages were perceived as darker than real stimuli. A possible consideration is that the real image stimuli were programmed to display a HSV value (brightness) of 10 % while the background of the OLED screen would show 0 % as the diodes remained off, whereas for afterimages, only the 0 % value black background was shown. The mean difference between real and afterimage ratings (~11 %) is numerically close to the 10 % display setting used for real rings; however, this similarity appears to be coincidental, as evidenced by the non-zero ratings for afterimages and the wide variability across participants.

Furthermore, adaptation reduced the time required for both stimuli to reach awareness and increased afterimage duration, suggesting that dark adaptation influences not just size scaling but also visual persistence. Notably, observers spent more time viewing afterimages than real

objects before initiating the size-matching adjustment, so longer viewing time cannot account for the superior size-distance scaling achieved with real objects.

### 4.2. Adapting to the dark improved size-distance scaling for both stimuli

Both real objects and afterimages were perceived more accurately in adapted darkness than in sudden darkness, though the effect was relatively small (~5 % reduction in error for real objects, ~10 % for afterimages). This supports the idea that even brief adaptation enhances sensitivity to environmental depth information, which in turn may facilitate residual depth scaling mechanisms. However, contrary to our hypothesis, afterimages did not benefit from adaptation more than real objects.

One possible explanation is that afterimages lack intrinsic depth structure, meaning that even with improved visual sensitivity, their placement in space remains ambiguous. Unlike real objects, which may benefit from contrast edges or weak shading in low-light conditions, afterimages lack physical presence in the environment and therefore do not afford the same access to depth information from environmental cues. These findings align with signal ambiguity theory, which posits that afterimages rely more heavily on contextual information to resolve their perceptual instability (Powell et al., 2012). Further, they are consistent with prior research demonstrating that afterimages are more susceptible to perceptual distortions in reduced cue environments (Edwards, 1953; Furedy & Stanley, 1970, 1971; Hastorf & Kennedy, 1957; Irwin, 1969; Millard et al., 2025).

### 4.3. Perceived size did not reflect retinal image size, even in sudden darkness

A key challenge in studying size-distance scaling in darkness is understanding exactly how the visual system compensates for missing depth cues. Familiar objects allow retinal image size to be used to estimate distance (Fisher & Sperandio, 2018; Gillam, 1995), but for unfamiliar stimuli such as the novel blue rings used here, the visual system may discount retinal size, because the same retinal angle can correspond to many real-world sizes at different distances (Knill, 2007; Mamassian & Landy, 2001; Sousa et al., 2011). Nevertheless, a possibility worth

considering is whether participants simply reproduced the retinal size they had just encoded during the matching phase. Mon-Williams and Tresilian (1999) indeed showed that, in low-cue visual scenes, remembered angular size can bias *delayed* verbal judgements of distance. In our experiment, distance was reported while the target was still visible, so that particular memory effect would not apply; nevertheless, could a parallel bias have influenced the subsequent size-matching task?

Given that the adjustment screen appeared less than a second after target offset and at the same physical distance as the target, it is possible that this brief pause may have encouraged participants to match the remembered angle in a more cognitive manner rather than making a match based on a remembered perception. In the former case, two signatures should have emerged: 1) near-perfect size estimates for real objects, because reproducing the constant 4.28° retinal angle yields the correct physical diameter at every viewing distance, and 2) a constant physical diameter across all distances for afterimages, because reproducing the constant 4.28° retinal angle yields the size of the afterimage inducer. Our data diverge from both predictions and show additional differences across adapted and sudden darkness. Thus, even if a cognitive influence could not be eliminated, we do not think it could account for the overall pattern of results obtained. Hence, it is our view that a more plausible explanation is that participants incorporated internal spatial assumptions into their perception, allowing some size-distance scaling to persist, even in sudden darkness.

When explicit cues from the environment and the object are unavailable, internal mechanisms influence perceived distance, which in turn impacts perceived size. Gogel (1965) proposed that individuals default to a specific distance tendency (SDT), where objects are perceived at a default distance in the absence of external references. This is thought to be driven by the resting state of oculomotor cues, particularly vergence and accommodation (Gogel & Tietz, 1977). Supporting this, vergence has been shown to play a critical role in size-distance scaling under reduced cue conditions (Foley, 1980; Hermans, 1937; Leibowitz & Moore, 1966; Mon-Williams et al., 1997). More recently, Sperandio et al. (2013) demonstrated that vergence was the primary driver of changes in perceived size when participants viewed afterimages in a darkened room with both eyes open. However, in the present study, individual differences in vergence and accommodation ability were not significantly associated with size or distance misperception. This may reflect a distinction between oculomotor capacity and the perceptual defaults underpinning SDT. While SDT may originate from the resting state of vergence and accommodation, it is not necessarily determined by how well those systems function during active viewing. Instead, it may reflect a habitual or internalised distance assumption that is invoked in the absence of external cues, regardless of the individual's convergence or accommodation range.

Prior work further suggests that SDT is not uniform across individuals. Millard et al. (2020) found that in complete visual deprivation conditions, participants consistently reported default afterimage sizes that did not match retinal image size, suggesting that they perceived afterimages at an internally assumed distance despite a lack of environmental depth cues. Furthermore, there was substantial individual variability in reported default sizes, implying that size-distance misperceptions in darkness depend on observer-specific perceptual strategies. Notably, the reported sizes always fell within plausible spatial limits of the testing environment. In line with this, Gogel (1969) suggested that an observer's knowledge or assumptions might influence SDT, though he maintained that these factors would not be the primary determinant of oculomotor resting position under reduced visual conditions.

Zhou et al. (2013) expanded on this idea by introducing the concept of intrinsic bias, arguing that the brain does not assume an unstructured perceptual space but instead relies on an internalized spatial model. Specifically, their findings suggest that the visual system defaults to perceiving a ground surface that is slanted upward with distance as a reference for distance perception. The present study provides evidence

supporting this theory, as participants tended to underestimate both size and distance for stimuli positioned beyond three meters, consistent with an assumption of an upward slanting spatial geometry. Notably, Zhou et al. (2013) used a blind walking task to gather data on perceived distance, whereas we used a verbal estimate. A weakness of verbal estimates is that they are considered more prone to cognitive bias than walking tasks (see Dong et al., 2023 for review). We take the similarity between these data across investigations as support for the perceptual judgements reported in this study as being accurate representations of what participants experienced in the dark.

Additionally, there was variability across participants in how much their judgements deviated from Emmert's law, which mirrors findings from our recent work (Millard et al., 2020, 2025). This is indicative of substantial individual differences in darkness misperception, particularly for afterimages. While some participants maintained size-distance scaling that was partially reflective of size constancy, others exhibited extreme deviations from Emmert's law, suggesting that perceptual scaling mechanisms in darkness are not uniform across individuals. Since afterimages lack external depth anchors, their perceived size may have been influenced by an observer's default assumptions about distance, particularly under sudden darkness conditions. This seems more likely than a purely oculomotor-driven specific distance tendency, as the presence of small luminous fixation points in this study likely prevented vergence and accommodation from reverting to a default position. Our prior investigations found notably worse accuracy for afterimages when projected in complete darkness without fixation points (Millard et al., 2025: 82 % deviation from Emmert's law versus the current 65 %) and when projected onto the back of the eyelids with closed eyes (Millard et al., 2020: 91 % deviation from Emmert's law).

Anecdotal remarks provided by participants during debriefing offered insight into the subjective experience of the darkness conditions and help contextualise the observed behavioural effects. Several participants reported that the adapted darkness condition, which allowed time for visual adjustment, felt more comfortable and less effortful than sudden darkness. Adapted darkness was described as relaxing and stabilising, with one participant noting, *"My eyes felt more relaxed after adjusting... I felt a lot more comfortable and less effort to complete the tasks."* In contrast, sudden darkness was often described as jarring or visually disorienting, prompting compensatory scanning for anchors. Participants frequently reported increased visual searching or instability in this condition, with one describing that, *"The sudden darkness was harsh and my eyes kept feeling like they needed to find something."* Participants also commented on differences in the clarity and stability of afterimages across conditions, with several describing them as more defined, solid, or easier to perceive in adapted darkness and more "smoky" or fleeting in sudden darkness.

With regard to perceiving the location of the stimuli in the testing space, participants described a range of confidence levels in judging distance across darkness conditions, but confidence did not always correspond with accuracy. Some felt they could "ballpark" distance or distinguish between close and far placements, while others described moments of clear misjudgement. One participant commented, *"It was harder to gauge distance... when the lights came on it was nowhere near as close or far as I thought,"* reflecting the perceptual distortion introduced by sudden darkness. These observations align with the idea that degraded environments introduce greater variability in depth estimation, and that internal confidence may not reliably reflect perceptual accuracy in the absence of strong external cues.

Although not formally analysed, these accounts provide useful context for interpreting the quantitative results and highlight the importance of considering the experiential qualities of darkness when evaluating perceptual mechanisms in reduced-cue environments.

#### 4.4. Within-condition effects of perceived brightness on distance judgments

Size and distance judgments were not correlated for either stimulus type, suggesting that size and distance scaling mechanisms are at least partially independent in darkness. This replicates our earlier observation with afterimages (Millard et al., 2025), but the lack of correlation for real objects was notably inconsistent with our prior investigation using the same apparatus and testing space, where size and distance judgments for real objects were highly consistent in sudden darkness. For a fuller discussion of task-related factors such as the use of magnitude estimates, we refer readers to Millard et al. (2025). The key methodological differences between these studies were (1) the presence of fixation points in the current study, and (2) a different sample of participants.

Therefore, one possibility is that the fixation point may have influenced depth perception strategies, altering how participants integrated available depth information in darkness. Alternatively, individual variation in distance judgments may be inherently large in the absence of strong depth cues, meaning that a different sample could yield different results. Interestingly, perceived brightness (value) was significantly associated with greater distance misperception in this study. Across conditions, real objects were perceived as brighter and better scaled than afterimages. The brightness effects described here therefore concern within-condition variability only. Specifically, two within-condition correlations emerged: in adapted darkness, afterimages judged brighter were associated with greater distance errors; in sudden darkness, the same was true for real objects. In both cases, participants who matched the stimuli to higher brightness values tended to show larger distance errors. While the correlation analyses used deviations from Emmert's law (i.e., overall amount of misperception rather than direction of the misperception) and therefore do not indicate whether stimuli were perceived as closer or farther than predicted, visual inspection of the distance scaling plots (Fig. 3) reveals that estimations of real stimuli consistently fell below the Emmert's law line (indicating a general underestimation of distance). This pattern suggests that real objects perceived as being brighter were also perceived as disproportionately closer, indicating a compression of perceived depth in low-light conditions. This relationship was not evident for afterimages, which showed minimal distance scaling across distances and no clear pattern of directional misperception; that is, afterimages appeared disproportionately far away at near and midrange distances, and disproportionately close at far distances.

Together, these findings suggest that increased brightness may interfere with distance perception for the real stimuli by exaggerating their apparent proximity, particularly in environments where external depth cues are reduced. This interpretation is consistent with earlier work (Egusa, 1982; Farnè, 1977) which found that when an object is perceived as figure and presented with strong contrast against a dark background, it is more likely to be judged as nearer. In the present study, the luminous real objects appeared against a black OLED screen, creating strong figure-ground contrast. Participants who perceived the real rings as brighter may have experienced enhanced figure salience, resulting in exaggerated proximity judgments. In contrast, afterimages, which are internally generated and lack physical luminance, likely produced weaker contrast with the background and were less able to engage contrast-based depth cues, helping to explain the lack of consistent directional misperception for these stimuli.

It is also important to consider that the distances tested in this study (approximately 2–6 m) exceed the range within which oculomotor cues such as vergence and accommodation provide reliable information, which is typically effective only up to approximately 2 m (Mon-Williams & Tresilian, 1999). Within this range, participants likely relied more on residual monocular cues or cognitive factors, such as expectations about the layout of the room or knowledge about changes in viewing distance, to estimate depth. When these already limited cues were paired with

increased perceived brightness and enhanced figure-ground contrast, the resulting perceptual salience may have biased judgments toward nearer perceived distances. In this way, perceived brightness may have interacted with depth cue limitations in darkness to compress perceived space, particularly for real objects, which had a defined physical presence and stood out against the background.

This suggests that brightness may actively interfere with size-distance scaling when an object has a defined physical presence. Prior research on car taillight perception in darkness found that brightness alone is a weak depth cue, meaning that the visual system may struggle to accurately interpret luminous stimuli when other depth cues are limited (Janssen et al., 1976). In the present study, the stronger correlation between brightness and distance misperception for real objects could indicate that when brightness competes with residual depth cues (e.g., vergence, contrast edges), it disrupts depth scaling rather than enhancing it.

Additional support for this idea comes from Morrison and Whiteside (1984), who demonstrated that even in the absence of rich visual cues, observers can use vergence to estimate the distance of a point light source in darkness, typically resulting in a compression of depth. Although the present study did not find any significant relationship between individual vergence ability and distance misperception, all participants exhibited normal to strong vergence function. This suggests that the observed effects may instead reflect the resting state of vergence (i.e., the default oculomotor posture that provides an internal depth reference when external cues are unavailable). When combined with increased stimulus brightness and contrast, this internal metric may have biased participants toward judging real objects as nearer than expected, particularly in sudden darkness.

For afterimages, the relationship appeared only under adapted darkness, where heightened sensitivity during dark adaptation may have made brighter afterimages appear more vivid but less well anchored in space, reducing accuracy. As afterimages lack intrinsic depth structure and do not produce contrast with the surrounding environment, brightness alone may be insufficient to drive depth misperception in the same way it appeared to for the real stimuli. Crucially, the actual physical value of the real stimuli did not change; all participants viewed the same dark blue stimuli (hue: 253°, saturation: 100 %, value: 10 %). This further supports the idea that brightness perception, rather than physical luminance, influenced distance scaling in darkness. Given that dark adaptation enhances retinal sensitivity, individual differences in the extent or speed of adaptation (see Hecht et al., 1937) may have contributed to variability in perceived brightness across participants, even when the physical stimulus remained constant.

Interestingly, participants who described the stimuli as particularly bright or vivid also tended to remark on the lack of contextual information in the environment, noting that while the object stood out, its grounding in the space was diminished. One participant reflected, “*The contrast of the objects was sharper... but I can't really see the screen. So, I didn't have anything else to give context,*” while another remarked, “*They looked closer and like they were floating.*” This aligns with our quantitative finding that participants who perceived the stimuli as brighter tended to make less accurate distance judgments, suggesting that heightened visibility in the absence of contextual anchors may actually impair spatial scaling. Rather than aiding perception, increased stimulus salience may have accentuated the object's isolation from the environment, leading to perceptual “float” or a misperception of its depth. Taken together, these findings highlight that although real objects (the perceptually brighter stimuli overall) showed superior scaling compared to afterimages, within each stimulus type participants who perceived the stimulus as brighter tended to make larger distance errors.

#### 4.5. Conclusion and future directions

This study advances our understanding of how the visual system processes size and distance in low-light environments, highlighting the

differential processing of real objects and afterimages. We provide novel evidence that even a brief period of dark adaptation facilitates small but significant improvements in size-distance scaling. Yet, afterimages do not uniquely benefit from adaptation, suggesting that their reliance on external depth cues extends beyond what mesopic adaptation alone can provide. Future research could investigate whether longer adaptation periods produce stronger effects, as well as explore the role of individual differences in specific distance tendency and intrinsic bias. Additionally, further work could examine the interaction between brightness and perceived depth, as the present study found that higher perceived brightness was linked to greater distance errors, particularly for real objects.

Ultimately, our findings suggest that size constancy mechanisms are closely tied to external depth cues rather than being an inherent, automatic process applied to all visual representations. Real objects maintained better size constancy than afterimages across conditions, reinforcing the idea that afterimages, when unsupported by robust environmental context, fail to maintain perceptual scaling in darkness. Importantly, these findings reflect mesopic visual processing (where both rods and cones contribute) and therefore speak to how the visual system operates in most real-world low-light conditions. Understanding perception under mesopic vision has practical relevance for nighttime navigation, driving, and environments with dynamic lighting, where partial adaptation and reduced cues are the norm rather than the exception.

#### CRedit authorship contribution statement

**Amy Siobhan Millard:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Irene Sperandio:** Writing – review & editing, Conceptualization. **Philippe A. Chouinard:** Writing – review & editing, Supervision, Conceptualization.

#### Informed consent

The privacy rights of human subjects have been observed. All participants gave informed, written consent to participant in the experiments. All participants consented to have their data published.

#### Ethics approval

The procedures used here were approved by La Trobe University's human Ethics Committee and were conducted in accordance with the 1964 Helsinki Declaration. Ethics reference: [HEC21153](#), ethics approved 22nd June 2021

#### Funding

This work was supported by funds from La Trobe University's School of Psychology and Public Health. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

The data supporting the findings of this study are available on the Open Science Framework (OSF) at [https://osf.io/79s3d/?view\\_only=0c34801ada814c5ebb6e726a630524e5](https://osf.io/79s3d/?view_only=0c34801ada814c5ebb6e726a630524e5).

#### References

- Andrews, D. P. (1964). Error-correcting perceptual mechanisms. *Quarterly Journal of Experimental Psychology*, 16(2), 104–115. <https://doi.org/10.1080/17470216408416355>
- Barbur, J. L., & Stockman, A. (2010). Photopic, Mesopic and scotopic vision and changes in visual performance. In D. A. Dartt (Ed.), *Encyclopedia of the Eye* (pp. 323–331). Academic Press. <https://doi.org/10.1016/B978-0-12-374203-2.00233-5>.
- Chalmers, E. L. (1952). Monocular and binocular cues in the perception of size and distance. *The American Journal of Psychology*, 65(3), 415–423. <https://doi.org/10.2307/1418762>
- Chalmers, E. L. (1953). The rôle of brightness in primary size-distance perception. *The American Journal of Psychology*, 66(4), 584–592. <https://doi.org/10.2307/1418954>
- Chen, J., Sperandio, I., & Goodale, M. A. (2018). Proprioceptive distance cues restore perfect size constancy in grasping, but not perception. *When Vision Is Limited. Current Biology*, 28(6), 927–932.e4. <https://doi.org/10.1016/j.cub.2018.01.076>
- Dong, B., Chen, A., Gu, Z., Sun, Y., Zhang, X., & Tian, X. (2023). Methods for measuring egocentric distance perception in visual modality. *Frontiers in Psychology*, 13, Article 1061917. <https://doi.org/10.3389/fpsyg.2022.1061917>
- Edwards, W. (1953). Apparent size of after-images under conditions of reduction. *The American Journal of Psychology*, 66(3), 449–455. <https://doi.org/10.2307/1418239>
- Egusa, H. (1982). Effect of brightness on perceived distance as a figure-ground phenomenon. *Perception*, 11(6), 671–676. <https://doi.org/10.1068/p110671>
- Emmert, E. (1881). Grossenverhältnisse der nachbilder. *Klinische Monatsblätter Fur Augenheilkunde*, 19, 443–450.
- Farné, M. (1977). Brightness as an indicator to distance: relative brightness per se or contrast with the background? *Perception*, 6(3), 287–293. <https://doi.org/10.1068/p060287>
- Fisher, C., & Sperandio, I. (2018). Familiar size effects on reaction time: When congruent is better. *Journal of Experimental Psychology: Human Perception and Performance*, 44(9), 1414–1425. <https://doi.org/10.1037/xhp0000543>
- Foley, J. M. (1980). Binocular distance perception. *Psychological Review*, 87, 411–434. <https://doi.org/10.1037/0033-295X.87.5.411>
- Furedy, J. J., & Stanley, G. (1970). The apparent size of “projected” afterimages under conditions where size-constancy holds. *Perception & Psychophysics*, 7(3), 165–168. <https://doi.org/10.3758/BF03208650>
- Furedy, J. J., & Stanley, G. (1971). More data and arguments for partial failure of Emmert's law under conditions of size constancy and veridical distance perception: Rejoinder to Teghtsoonian's comments. *Perception & Psychophysics*, 10(2), 99–100. <https://doi.org/10.3758/BF03214325>
- Gillam, B. (1995). Chapter 2—the perception of spatial layout from static optical information. In W. Epstein, & S. Rogers (Eds.), *Perception of Space and Motion* (pp. 23–67). Academic Press. <https://doi.org/10.1016/B978-012240530-3/50004-3>.
- Gogel, W. C. (1965). Equidistance tendency and its consequences. *Psychological Bulletin*, 64, 153–163. <https://doi.org/10.1037/h0022197>
- Gogel, W. C. (1969). The sensing of retinal size. *Vision Research*, 9(9), 1079–1094. [https://doi.org/10.1016/0042-6989\(69\)90049-2](https://doi.org/10.1016/0042-6989(69)90049-2)
- Gogel, W. C., & Tietz, J. D. (1977). Eye fixation and attention as modifiers of perceived distance. *Perceptual and Motor Skills*, 45(2), 343–362. <https://doi.org/10.2466/pms.1977.45.2.343>
- GraphPad Software. (2014). *GraphPad Prism (Version 6) [Computer software]*. <https://www.graphpad.com/>.
- Gregory, R. L. (1973). *Eye and brain: The psychology of seeing* (Vol. 80). Princeton University Press.
- Gregory, R. L., Wallace, J. G., & Campbell, F. W. (1959). Changes in the size and shape of visual after-images observed in complete darkness during changes of position in space. *Quarterly Journal of Experimental Psychology*, 11(1), 54–55. <https://doi.org/10.1080/17470215908416288>
- Hastorf, A. H., & Kennedy, J. L. (1957). Emmert's law and size-constancy. *The American Journal of Psychology*, 70(1), 114–116. <https://doi.org/10.2307/1419240>
- Hastorf, A. H., & Way, K. S. (1952). Apparent size with and without distance cues. *The Journal of General Psychology*, 47(2), 181–188. <https://doi.org/10.1080/00221309.1952.9710662>
- Hecht, S., Haig, C., & Chase, A. M. (1937). The influence of light adaptation on subsequent dark adaptation of the eye. *Journal of General Physiology*, 20(6), 831–850. <https://doi.org/10.1085/jgp.20.6.831>
- Hermans, T. G. (1937). Visual size constancy as a function of convergence. *Journal of Experimental Psychology*, 21, 145–161. <https://doi.org/10.1037/h0058367>
- Holway, A. H., & Boring, E. G. (1941). Determinants of apparent visual size with distance variant. *The American Journal of Psychology*, 54(1), 21–37. <https://doi.org/10.2307/1417790>
- Irwin, R. J. (1969). Emmert's law as a consequence of size constancy. *Perceptual and Motor Skills*, 28(1), 69–70. <https://doi.org/10.2466/pms.1969.28.1.69>
- Ishihara, S. (1918). Tests for color blindness. *American Journal of Ophthalmology*, 1(5), 376.
- Ittelson, W. H. (1951). Size as a cue to distance: Static localization. *The American Journal of Psychology*, 64(1), 54–67. <https://doi.org/10.2307/1418595>
- Janssen, W. H., Michon, J. A., & Harvey, L. O. (1976). The perception of lead vehicle movement in darkness. *Accident Analysis & Prevention*, 8(3), 151–166. [https://doi.org/10.1016/0001-4575\(76\)90017-8](https://doi.org/10.1016/0001-4575(76)90017-8)
- JASP Team. (2024). *JASP (Version 0.18.3) [Computer software]*. <https://jasp-stats.org/>.
- Kalloniatis, M., & Luu, C. (1995). Light and dark adaptation. In H. Kolb, E. Fernandez, B. Jones, & R. Nelson (Eds.), *Webvision: The Organization of the Retina and Visual System*. University of Utah Health Sciences Center.
- Kilpatrick, F. P., & Ittelson, W. H. (1953). The size-distance invariance hypothesis. *Psychological Review*, 60, 223–231. <https://doi.org/10.1037/h0060882>

- Knill, D. C. (2007). Learning Bayesian priors for depth perception. *Journal of Vision*, 7(8), 13. <https://doi.org/10.1167/7.8.13>
- Leibowitz, H., & Moore, D. (1966). Role of changes in Accommodation and Convergence in the perception of Size\*. *JOSA*, 56(8), 1120–1123. <https://doi.org/10.1364/JOSA.56.001120>
- Lichten, W., & Lurie, S. (1950). A new technique for the study of perceived size. *The American Journal of Psychology*, 63(2), 280–282. <https://doi.org/10.2307/1418936>
- Mamassian, P., & Landy, M. S. (2001). Interaction of visual prior constraints. *Vision Research*, 41(20), 2653–2668. [https://doi.org/10.1016/S0042-6989\(01\)00147-X](https://doi.org/10.1016/S0042-6989(01)00147-X)
- Millard, A. S., Sperandio, I., & Chouinard, P. A. (2020). The contribution of stereopsis in Emmert's law. *Experimental Brain Research*, 238(4), 1061–1072. <https://doi.org/10.1007/s00221-020-05747-5>
- Millard, A. S., Sperandio, I., & Chouinard, P. A. (2025). The size-distance scaling of real objects and afterimages is equivalent in typical but not reduced visual environments. *Experimental Brain Research*, In press. <https://doi.org/10.1007/s00221-025-07064-1>
- Mon-Williams, M., & Tresilian, J. R. (1999). The size-distance paradox is a cognitive phenomenon. *Experimental Brain Research*, 126(4), 578–582. <https://doi.org/10.1007/s002210050766>
- Mon-Williams, M., Tresilian, J. R., Plooy, A., Wann, J. P., & Broerse, J. (1997). Looking at the task in hand: Vergence eye movements and perceived size. *Experimental Brain Research*, 117(3), 501–506. <https://doi.org/10.1007/s002210050246>
- Morgan, M. J. (1992). On the scaling of size judgements by orientational cues. *Vision Research*, 32(8), 1433–1445. [https://doi.org/10.1016/0042-6989\(92\)90200-3](https://doi.org/10.1016/0042-6989(92)90200-3)
- Morrison, J. D., & Whiteside, T. C. D. (1984). Binocular cues in the perception of distance of a point source of light. *Perception*, 13(5), 555–566. <https://doi.org/10.1068/p130555>
- Neely, J. C. (1956). The R.A.F. near-point rule. *British Journal of Ophthalmology*, 40(10), 636–637. <https://doi.org/10.1136/bjo.40.10.636>
- Norman, J. F., Baig, M., Eaton, J. R., Graham, J. D., & Vincent, T. E. (2022). Aging and the visual perception of object size. *Scientific Reports*, 12(1), 17148. <https://doi.org/10.1038/s41598-022-22141-z>
- Over, R. (1960). Size and distance judgements under reduction conditions. *Australian Journal of Psychology*, 12(2), 162–168. <https://doi.org/10.1080/00049536008255051>
- Powell, G., Bompas, A., & Sumner, P. (2012). Making the incredible credible: Afterimages are modulated by contextual edges more than real stimuli. *Journal of Vision*, 12(10), 17. <https://doi.org/10.1167/12.10.17>
- Predebon, J. (1992). The role of instructions and familiar size in absolute judgments of size and distance. *Perception & Psychophysics*, 51(4), 344–354. <https://doi.org/10.3758/BF03211628>
- Snellen, H. (1862). *Letterproeven, tot bepaling der gezigtsscherpte* (Vol. 1). J. Greven.
- Sousa, R., Brenner, E., & Smeets, J. B. J. (2011). Judging an unfamiliar object's distance from its retinal image size. *Journal of Vision*, 11(9), 10. <https://doi.org/10.1167/11.9.10>
- Sperandio, I., & Chouinard, P. A. (2015). The mechanisms of size constancy. *Multisensory Research*, 28(3–4), 253–283. <https://doi.org/10.1163/22134808-00002483>
- Sperandio, I., Kaderali, S., Chouinard, P. A., Frey, J., & Goodale, M. A. (2013). Perceived size change induced by nonvisual signals in darkness: The relative contribution of vergence and proprioception. *Journal of Neuroscience*, 33(43), 16915–16923. <https://doi.org/10.1523/JNEUROSCI.0977-13.2013>
- Vision Assessment Corporation. (n.d.). *Random Dot 3 Stereo Test*. <https://www.visionassessment.com/random-dot-3-s>.
- Wang, G., Zheng, C., Wu, X., Deng, Z., Sperandio, I., Goodale, M. A., & Chen, J. (2024). The contribution of semantic distance knowledge to size constancy in perception and grasping when visual cues are limited. *Neuropsychologia*, 196, Article 108838. <https://doi.org/10.1016/j.neuropsychologia.2024.108838>
- Weintraub, D. J., & Gardner, G. T. (1970). Emmert's laws: size constancy vs. optical geometry. *The American Journal of Psychology*, 83(1), 40–54. <https://doi.org/10.2307/1420854>
- Zhou, L., He, Z. J., & Ooi, T. L. (2013). The visual system's intrinsic bias and knowledge of size mediate perceived size and location in the dark. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39(6), 1930–1942. <https://doi.org/10.1037/a0033088>