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Ocular compensation for alternating myopic and hyperopic defocus

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Abstract

During development, the eye grows under visual feedback control, as shown by its compensating for defocus imposed by spectacle lenses. Under normal conditions the sign and magnitude of defocus vary with viewing distance, accommodative status and other factors. To explore how periods of myopic and hyperopic defocus are integrated over time we presented rapidly alternating episodes of myopic and hyperopic defocus by sequentially illuminating a nearby scrim and the wall beyond it to chick eyes wearing lenses that put the far point between the two surfaces. We found that equal periods of myopic and hyperopic defocus generally led to compensatory hyperopia, showing that myopic defocus had a disproportionate effect. Furthermore, the degree of hyperopia depended on the frequency of alternation: low frequencies (1 cycle/30 min) resulted in more hyperopia, whereas at high frequencies (1 cycle/s) the myopic and hyperopic defocus nearly cancelled each other. If similar temporal integration effects apply to humans, they may help explain why brief accommodation events may not influence lens-compensation and why a child's total reading time may be a poor predictor of myopic progression.
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1. Introduction

Decades of experimental work in animals has provided strong evidence that emmetropization, the reduction in refractive error during development, is an active, visually guided process (reviewed by Wallman & Winawer, 2004; Wildsoet, 1997). Specifically, eye length and refractive status can be altered by imposing defocus with spectacle lenses or contact lenses (chicks, Schaeffel, Glasser, & Howland, 1988; Irving, Sivak, & Callender, 1992; rhesus monkeys, Hung, Crawford, & Smith, 1995; marmosets, Whatham & Judge, 2001; guinea pigs, McFadden, Howlett, & Mertz, 2004). Under

these conditions, the eye speeds or slows its rate of elongation to grow into focus for the combined power of the spectacle lens and the eye's lens and cornea, suggesting that a feedback loop using visual cues as an error signal regulates eye growth.

One challenge faced by such a feedback control system is how to derive a useful error signal from a highly variable and often transient input (defocus, or some visual signal that depends on defocus). For example, a hyperopic eye (as usually found in young animals) will experience hyperopic defocus when looking at distant objects, but when it is focused on nearby objects, distant objects will be myopically defocused. Despite the complex pattern of input, over time animals fitted with spectacles lenses can compensate quite accurately for the power of the lens (Irving et al., 1992; Smith & Hung, 1999). How does the eye do this? Does each brief episode of blur change the momentary direction of eye growth? Do myopic and hyperopic defocus cancel, or does one predominate?

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Recent experiments suggest that the emmetropization system uses a method of integration more complex than computing a linear sum of all the blur it experiences. First, it has been shown that in chicks, as little as 2 min of lens-wear every hour can stimulate nearly as good compensation as does full-time lens-wear, and the compensation for imposed defocus of either sign is comparable, if there is no other visual input (Winawer & Wallman, 2002). In contrast, a strong asymmetry is found if the lens-wear alternates between myopic defocus imposed by positive lenses and hyperopic defocus imposed by negative lenses: the eye compensates for the positive lens, even if there is five times longer negative than positive lens-wear. In the extreme, in chicks as little as four 2-min periods of positive lens-wear per day can outweigh the effects of negative lenses worn the rest of the day (Zhu, Winawer, & Wallman, 2003). These results all suggest that the emmetropization mechanism is particularly sensitive to myopic defocus. Given that humans would almost certainly have the equivalent of these eight minutes of myopic defocus over a day, it is puzzling why myopia developing in children would not be stopped dead in its tracks. One possibility is that the asymmetries reported in the animal literature apply only to extended periods of defocus; perhaps the emmetropization mechanism either ignores very brief periods of defocus altogether or integrates them in a more balanced way.

In this paper, we address the issue of how the eye's emmetropization system integrates very brief periods of defocus alternating in sign. We present results from a series of experiments in which we put chicks in a controlled visual environment for 30 min at a time. During these periods, we rapidly alternated the sign of defocus by alternately illuminating a nearby scrim (imposing hyperopic defocus) or a more distant wall (imposing myopic defocus). By doing so, we were able to address whether (1) the eye weighs short periods of positive and negative defocus equally and (2) whether the weighting depends on the frequency of alternation.

2. Methods

White Leghorn chickens were obtained either as eggs or 1 day after hatching from Truslow Farms (Hyline-W98-strain; Chestertown, MD), except for group 8 (Cornell K-strain White Leghorns, obtained from Cornell University, Ithaca, NY). All chicks were either 6 or 7 days post-hatching at the start of experiments, all of which lasted 3 days. At the start and end of each experiment, both eyes had their refractive error measured using a modified Hartinger Refractometer (Wallman & Adams, 1987) and their axial dimensions measured using high frequency A-scan ultrasound (Nickla, Wildsoet, & Wallman, 1998; Wallman &

Adams, 1987). Total ocular length was defined as the distance from the front of the cornea to the back of the sclera (unlike clinical measurements, which are made to the front of the retina, thereby not including retinal, choroidal, or scleral thickness). Measurements were made under 1.5% Halothane anesthesia, without cycloplegia, and were made at the same time of day at the start and the end of the experiment. Plastic 12 mm lenses or black plastic occluders were fitted by gluing the lens to a Velcro ring and then fixing the ring to a mating Velcro ring, glued to the feathers around the eye (for more details, see Wildsoet & Wallman, 1995).

During the experiments, chicks were housed in groups in light-proof chambers in darkness, except for eight 30-min periods each day. During four of these periods, chicks were placed in a two-drum system (Fig. 1, see below), wearing a +6 diopter spectacle lens on one eye and an opaque black occluder on the other.
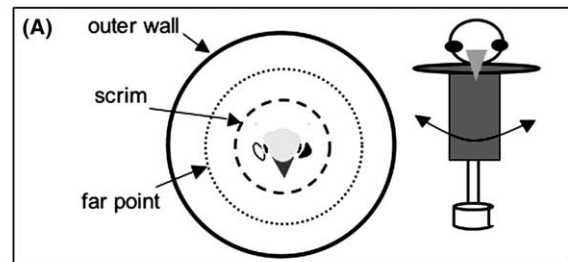
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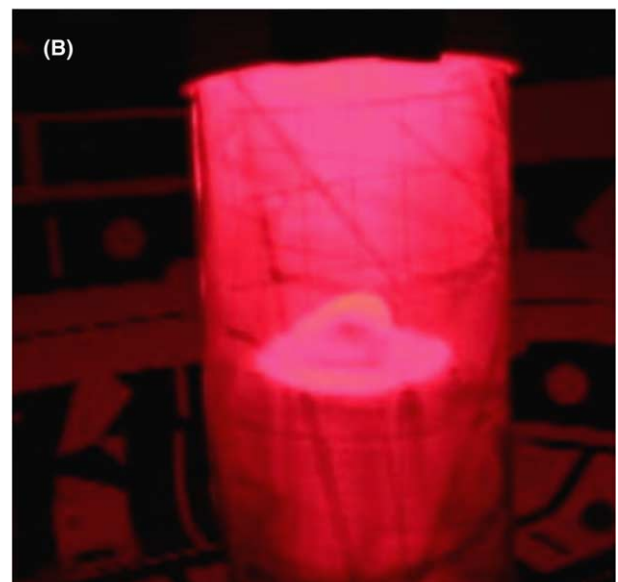
photograph of scrim from inside large drum

Fig. 1. Two-drum system. (A) Schematic: The opaque outer wall of the two-drum system was 30 cm from the drum center, and the inner scrim was 5 cm from the center. The far point falls between the two surfaces (16.7 cm for an unaccommodated emmetropic eye). Chicks were placed in the center and were rotated to encourage them to stay awake and look at the walls. (B) Photograph with inner scrim illuminated and the outer wall in the background.