Emmetropisation responses when visual information is presented at only one or two near target planes in chick*

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**Purpose:** When visual information is confined to one object plane and zero or hyperopic defocus is present, emmetropisation is directed towards this plane, when myopic defocus is present, emmetropisation processes fail. We investigated the effect of introducing information at a second nearer plane on emmetropisation responses under these conditions.

**Methods:** The visual environment was controlled using lenses (+30 D, +40 D and +50 D) and cones with a Maltese cross target (MX) at one or two distances. Four different target configurations were used: 1. a single target was located at 3.3 cm, 2. a vertical hemi-field target was added at 2.5 cm, 3. a transparent target was added at 2.5 cm or 4. a single target was located at 2.5 cm. An additional cone length of 4.0 cm and nearer target distance of 3.3 cm was used with the +50 D lens. The imaging devices were applied monocularly to eight-day-old chicks and worn for four days. At the end of the treatment, refractive errors and eye growth were measured. Potential regional differences in growth were also assessed.

**Results:** The configuration of the target and the interaction between target configuration and lens power had significant refractive and axial growth effects. With a single target plane, myopic and hyperopic defocus resulted in myopia. When defocus was experienced at two planes, refractive errors shifted towards the plane with the lower defocus and emmetropisation responses, although still not normal, were more consistent.

**Conclusions:** When visual information is provided at two distances, the target with the lesser incident defocus has the greater influence on the resultant refractive error. Emmetropisation responses are more accurate when information is presented at many distances.

Key words: chick, defocus, emmetropisation, myopia

The situation where objects at all distances in the environment are focused clearly by the eye allows for optimal functioning. For most vertebrates, this involves having an emmetropic (or close to emmetropic) distance refractive state and engaging the accommodative mechanism for nearer objects. Emmetropisation processes, which act to achieve emmetropia by adjustment of eye growth, are known to exist (see Goss¹ for review). In animal models this mechanism can compensate for artificial refractive errors induced by spectacle lenses.²⁴ In young chicks, induced errors as high as +15 D and -15 D can be accurately compensated for in a very short period of time, such that with the lenses in place the eye is essentially emmetropic.⁵⁶

In the normal situation, it appears that eye growth is tuned to distant objects, even though objects at nearer distance are...
viewed frequently. However, in the case where vision is limited to one nearer distance the emmetropisation process shifts its end-point to this near distance. The emmetropisation end-point appears to be adjusted to reflect the corresponding incident optical vergence at the eye. As visual information is available at only one distance, the information presented at this plane and its distance from the eye now become the critical factors for emmetropisation.

Another characteristic of this paradigm, where visual information is confined to one object plane, is that the ability of the emmetropisation process to function normally is compromised. When zero, hyperopic defocus or only small amounts of myopic defocus are incident at the target, consistent emmetropisation processes are observed. However, when myopic defocus is present, even at normally well-compensated levels, the emmetropisation processes break down and myopia rather than hyperopia results.8,9

We sought to determine the effect of introducing information at one additional nearer plane on emmetropisation responses under these conditions. We were interested in answering the question: is visual information at two distances the least required for the normal functioning of the emmetropisation system? We have previously shown that when additional information is added beyond the main target plane, the emmetropisation end-point is shifted towards the added information.10 However, in this situation further information was added at a range of distances. It does not automatically follow that the same effect would occur under the more restrictive visual conditions used here.

In addition, it has been shown that when myopic and hyperopic defocus (that is, errors that result in opposite growth responses) are presented in alternating fashion across a day, the emmetropisation end-point is biased towards the myopic situation (that is, hyperopia results).11 Even if hyperopic defocus is experienced for five times as long as the myopic defocus, the effect of the myopic defocus is dominant. This is consistent with findings that short periods of normal vision prevent lens-induced-myopia rather than lens-induced-hyperopia12 and that short periods of occluder removal prevent form-deprivation myopia.13 In these situations, myopic defocus appears to provide the greater signal to the emmetropisation system and thus has the greater effect on the underlying growth of the eye. We also sought to determine what would happen when different amounts and types of defocus were presented simultaneously in two halves of the visual field.

MATERIALS AND METHODS

Animals
Male, Rhode Island Red—Rhode Island White cross chickens (Gallus gallus domesticus) were obtained from Nelbex Hatchery (Brisbane, Australia) on the day of hatching. Chicks were reared in temperature-controlled cages (30 degrees Centigrade) and provided with food and water ad libitum. Bright illumination (1,000 lux at the level of the food troughs) was provided by overhead fluorescent lights set to a 12-hour diurnal light cycle.

Treatments
We used a cone-shaped imaging system, which we have reported previously,8-10 to control the visual environment. Our modifications included the addition of a nearer semi-circular target plane (hemi-field) or transparent nearer target (Figure 1). The plane at the end of the cone and the nearer plane (hemi-field or transparent) were printed with a black and white complex Maltese cross target (MX). The cones...
were made from grey translucent polyethylene and provided a field of view of approximately 60 degrees. To alter the amount of defocus incident on each plane we used positive lenses of three high powers (+30 D, +40 D and +50 D) (Igel, Singapore) and a range of cone lengths. The lenses were made from PMMA material to a modified human contact lens design and were attached to the chicks by velcro rings. When applied in this manner, the lens vertex distance was 3.5 mm.

Four different target configurations were used in combination with each of the three lens powers:
1. the target was located at a single plane at 3.3 cm
2. a vertical hemi-field MX target was added at 2.5 cm
3. a transparent MX target was added at 2.5 cm
4. the target was located at a single plane at 2.5 cm.

Three additional target configurations were used with the +50 D lens power:
1. the target was located at a single plane at 4 cm
2. a vertical hemi-field MX target was added at 3.3 cm
3. a transparent MX target was added at 3.3 cm.

The imaging devices were applied monocularly to eight-day-old chicks (n = 7 to 9 per treatment group) and worn for 4.5 days.

The defocus on each target plane can be calculated using the power of the applied lens and incident optical vergence corresponding to each target distance. For the combinations of lens power and target distances used here, thin lens approximations and thick lens step along vergence calculations give defocus values, which differ by up to seven dioptres (the shorter the cone and more powerful the lens, the greater the difference). Using thin lens formulae, the +30 D and +40 D lenses appear to induce zero defocus, when targets are positioned at 3.3 cm and 2.5 cm, respectively. Similarly, with a +30 D lens, a target plane at 2.5 cm would have 10 D of induced hyperopic defocus; a +40 D lens at 3.3 cm would have 10 D of myopic defocus and with a +50 D lens, a plane at 2.5 cm would have 10 D of myopic defocus, a plane at 3.3 cm, 20 D of myopic defocus and one at 4 cm, 25 D of myopic defocus.

In comparison, thick lens formula and step along ray tracing give relatively more hyperopic defocus at the corneal plane. The lens power cone length combinations that appeared to have zero defocus using the thin lens approximations have significant levels of calculated induced defocus. With the +30 D lens, the 3.3 cm target has 2.81 D of hyperopic defocus and 12.64 D when the target is placed at 2.5 cm. For the +40 D lens, the eye experiences 4.95 D of hyperopic defocus for the 2.5 cm target position and 5.89 D of myopic defocus for the 3.3 cm target. In the case of the +50 D lens, values are +1.77 D, +13.52 D and +20.50 D with 2.5 cm, 3.3 cm and 4.0 cm target distances, respectively. As the thick lens step along formula takes into account factors such as lens radii of curvature, lens thickness, posterior lens vertex distance and the position of the eye’s entrance pupil, we have used these calculations when interpreting refraction and biometry data. Small errors in lens and target position will also have large vergence effects that could alter the amount of defocus on the target from that calculated.

**Measurements and analysis**

Axial lengths and refractive errors were measured using A-scan ultrasonography (10 MHz Panametrics, Massachusetts) and streak retinoscopy (Heine Beta 200, Munich), respectively, under two per cent isoflurane anaesthesia (in oxygen). For each treatment, interocular differences (that is, differences between treated and fellow eyes) were calculated for refractive error and axial length data. We used interocular difference data as a measure of the effect of the optical treatment, as is usual in lens wear experiments. The different lens and target treatments were compared using a two-way ANOVA (three lens powers and four target designs). One-way ANOVAs were used to assess the effect of target conditions for each lens power and the additional +50 D long cone data. The effect of varying the amount of hyperopic or myopic defocus at the target plane was also assessed using one-way ANOVA.

**RESULTS**

Target configuration (RE: p = 0.001, AL: p = 0.003) and the interaction between target configuration and lens power (RE: p = 0.0004, AL: p < 0.001), but not lens power alone (RE: p = 0.636, AL: p = 0.161),
had significant effects on refractive error and axial length (two factor ANOVA). The different combinations of target distance and target design used here produced significantly different refractive effects for all lens powers (+30 D, +50 D), except the +40 D lens treatment (Table 1). Refractive data for the single plane treatments, refractive data for the two plane treatments, axial length data and regional eye growth data are presented.

**Single target plane**

As has been shown previously, myopic (equivalent to a positive lens) and hyperopic (equivalent to a negative lens) defocus resulted in myopia under the visual conditions employed here (Table 1, Figure 2). There were three single target conditions where hyperopic defocus was produced at the target plane, the defocus ranging from -2.81 D to -12.64 D in magnitude. In addition, there were four treatments with myopic defocus, ranging from +1.77 D to +20.50 D. In no condition was there zero defocus at the target plane.

In one of the three hyperopic defocus conditions, the chicks on average became myopic (+30 D, 2.5 cm cone; -3.89 ± 3.04 D), while in the other two conditions, refractions were on average emmetropic (+40, 2.5 cm cone; 0.50 ± 2.13 D) or very slightly hyperopic (+30 D, 3.3 cm cone; 1.44 ± 1.51 D) (Table 1). Chicks experiencing the greater hyperopic defocus (-12.64 D) were the most myopic (-3.89 ± 3.04 D, p = 0.0002). For these treatments two out of nine (+30 D, 3.3 cm), one out of eight (+40 D, 2.5 cm) and zero out of eight (+30 D, 2.5 cm) chick’s refractive errors coincided exactly with the target plane (Figure 2Ai, 2Aiv and 2Biv). Four out of nine (+40 D, 3.3 cm), three out of eight (+50 D, 2.5 cm) and eight out of eight (+30 D, 2.5 cm) showed a refractive shift in the correct direction for eventual emmetropisation to the single target plane.

There were four single plane treatments where myopic defocus was present: +40 D at 3.3 cm (+4.95 D) and +50 D lens at 2.5 cm (+1.77 D), 3.3 cm (+13.52 D) and 4.0 cm (+20.50 D). In all but one of these myopic defocus treatments (+50 D, 2.5 cm; 1.53 ± 2.87 D), the average refractive error was myopic. The mean amount of myopia induced varied from two to seven dioptres (Table 1), with greater amounts of myopia being associated with greater amounts of myopic defocus (p = 0.008). Only for the +50 D, 2.5 cm treatment where the amount of myopic defocus was low (+1.77 D) did chicks (four out of eight, Figure 2Civ) develop enough hyperopia so that the far point coincided with the target. In fact in many cases (4/9 +40 D, 3.3 cm; 4/8 +50 D, 3.3 cm; 6/8 +50 D, 4.0 cm), the refractive change was in the direction opposite to that required for emmetropisation to the target plane. This is highlighted in Figure 3, where it is obvious that for myopic defocus the refractive error changes are not correlated to the type and amount of defocus. In the presence of a single target plane, eyes experiencing medium to high amounts of myopic defocus could not detect the type of defocus and did not emmetropise correctly. Refractive changes were usually consistent with axial length changes (Figure 2 and Table 2).

**Two planes (hemi-field, transparent)**

As a rule, introducing a second plane had only a small effect on the chicks’ refractive errors. Except in the case of the +50 D, longer cone treatment groups, these changes could usually be predicted by the eye growth response to the two single planes that were at the same distance as the
two planes used to design the composite targets (Table 1, Figure 2 and Figure 3).

For the +30 D hemi-field treatment results were more variable than with a single plane (SD: 5.1 D compared with 1.5 D and 3.0 D). Three quarters (6/8, Figure 2Aii) of the chicks’ far points were closer to the further plane (-2.81 D) and only one quarter (2/8) were closer to the nearer plane (-12.64 D); some remained nearly emmetropic and some became very myopic. The mean resultant refractive error (-2.53 ± 5.08 D) lay between the refractive shifts that occurred in response to the two single planes that comprised the target. The transparent target was not as effective at shifting the refractive error (p = 0.040), eight out of eight chicks remaining essentially focused on the further opaque target and had low hyperopic refractive errors (Figure 2Aiii).

A similar pattern of results was observed for the +40 D lens treatments (Figure 2B). The hemi-field near target again appeared
more effective at shifting the refraction towards it than the transparent plane (-1.61 ± 3.23 D compared with 1.39 ± 1.88 D), although here the difference was not significant. Again, the mean refractive errors of these two conditions were between those that occurred in response to the two single planes that comprise them. For the hemi-field condition, the refractive error of five out of eight chicks was closer to the nearer plane, whereas for the transparent plane refractive errors of seven out of eight chicks were closer to the further plane (compare Figures 2Bii and 2Biii). The introduction of the second plane appeared to reduce the variability of results observed with the +40 D, 3.3 cm condition (SD ±3.23 D and ±1.88 D compared with ±6.20 D, Table 1).

Again, a similar pattern was observed for the +50 D lens and short cone treatment (Figure 2C). Even though greater myopia occurred in response to the single further plane (-6.06 ± 5.35 D), the two hemi-field planes and additional transparent targets prevented the myopia (2.11 ± 3.59 D and 3.05 ± 2.65 D, respectively) (Table 1). Refractive errors of these two groups were only slightly more hyperopic than that observed with the sole nearer plane. This time both types of near plane were as effective in terms of controlling the refractive change and produced significantly less myopia than the single far plane chicks (transparent and hemi-field, p = 0.0001).

The +50 D lens was also applied with a longer four centimetre cone. In this case, the introduction of either a nearer hemi-field plane or a translucent target was not sufficient to eliminate the myopia, though it was reduced. The average remaining amounts of myopia (-1.82 ± 2.49 D and -2.44 ± 3.63 D, respectively) in the two plane conditions were much less than that observed with either single plane alone (further: -7.44 ± 5.80 D, nearer: -6.06 ± 5.35 D) (Table 1) and again the variability in the data was reduced. However, because of the high standard deviations in the single plane groups, the reduction in myopia did not reach statistical significance. In this case the refractive errors did not lie between those observed with the two single plane targets. No chick developed

Figure 3. Summary graphs showing the mean (± SE) difference between treated and non-treated eyes (A) refractive error and (B) axial length as a function of the amount of defocus induced at the target plane. When two planes are present, the data are displayed in the middle of the two-defocus levels that correspond to each plane; the horizontal double arrows indicate this. The dotted oblique line represents the expected emmetropisation responses, if eyes emmetropise to the optical vergence incident on the single plane or to the average of the two planes. In only a few cases the eye’s refractive errors shifted as expected, based on emmetropisation responses observed with lenses in normal visual environments.
enough hyperopia to make its refractive error coincident with the target plane (Figure 2D).

The results observed with the two plane hemi-field target and two plane translucent target were not always exactly the same. Eyes tended to be slightly more hyperopic in the transparent plane situation relative to the two plane hemi-field target \( (p = 0.029) \). For example, for the +30 D and +40 D lenses the differences were 4.87 D and 3.00 D, while for the +50 D treatments no difference in these two conditions was observed (Table 1, Figure 3).

### Axial length changes

Refractive changes were usually consistent with measured axial length changes (Figure 2 and Table 2). The large myopic refractive errors observed for +50 D, 3.3 cm and +50 D, 4.0 cm single plane groups were reflected in elongated axial lengths \( (0.30 \pm 0.27 \text{ mm} \text{ and } 0.41 \pm 0.28 \text{ mm}, \text{ respectively}) \), while hyperopic errors were usually associated with shorter axial lengths (for example, +30 D, 3.3 cm; +50 D, 2.5 cm). The reduction in myopia with the hemi-field and transparent target conditions was reflected in the reduced axial elongation they produced (for example, +50 D, 3.3 cm single near plane, 0.30 mm compared with +50 D two hemi-fields, 0.16 mm). Except for the +30 D translucent versus hemi-field condition, where refractive error differences between treatment groups were significant but axial length changes were not, if refractive error difference were significant, so too were the axial length changes.

### Regional eye growth changes

Eyes wearing the +30 D, hemi-field targets showed regional differences in eye growth. In three of four cases, the temporal part of the retina, which experienced the greater hyperopic defocus, was longer (by \( 0.16 \pm 0.02 \text{ mm} \) and more myopic (by \( 3.67 \pm 2.24 \text{ D} \)). This regional variation was not observed with +50 D, hemi-field targets where both halves of the eye experienced high levels of myopic defocus. Axial lengths were elongated by \( 0.44 \pm 0.44 \text{ mm} \), and there was no consistent nasal to temporal difference. In this case, refractive errors were myopic irrespective of measurement location (nasal to temporal difference: \( 1.42 \pm 3.72 \text{ D} \)).

### DISCUSSION

When visual information is provided at two distances, the amount of defocus experienced at each affects the resultant refractive error. This is consistent with data where the cone is closed with a translucent target so a single near plane and distance viewing are possible.\(^7\)

Again, we found that under these restricted visual conditions the ability to emmetropise to myopic defocus was severely compromised, with animals becoming myopic rather than hyperopic. Hyperopia was induced only in the lowest myopic defocus condition (+50 D, 2.5 cm, +1.82 D); slightly more myopic defocus (+40 D, 3.3 cm, +4.95 D) resulted in myopia. This difference in response presumably reflects the chicks naturally occurring low hyperopic refractive errors and limited capacity to negatively accommodate.\(^7\) The addition of information at one nearer distance inhibited some of this myopia development, that is, the additional target plane appeared to provide more information to the emmetropisation system. However, responses were still not the same as those observed with lenses and unrestricted vision.\(^23,6\) In the two plane situation, hyper-

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**Table 2. Axial length differences between cone wearing and untreated eyes (mean ± SD)**

<table>
<thead>
<tr>
<th>Lens Power (D)</th>
<th>Far plane (3.3 cm)</th>
<th>2 Plane hemi-field</th>
<th>Transparent near plane</th>
<th>Near plane (2.5 cm)</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far plane</td>
<td>-0.06 ± 0.09</td>
<td>-0.04 ± 0.27</td>
<td>* 0.30 ± 0.27</td>
<td>-0.17 ± 0.15</td>
<td>0.009</td>
</tr>
<tr>
<td>2 Plane</td>
<td>0.25 ± 0.33</td>
<td>-0.01 ± 0.19</td>
<td>0.02 ± 0.31</td>
<td>0.00 ± 0.11</td>
<td>0.164</td>
</tr>
<tr>
<td>Transparent</td>
<td>-0.07 ± 0.07</td>
<td>-0.03 ± 0.12</td>
<td>-0.20 ± 0.20</td>
<td>-0.22 ± 0.16</td>
<td>0.081</td>
</tr>
<tr>
<td>Near plane</td>
<td>-0.17 ± 0.15</td>
<td>0.00 ± 0.11</td>
<td>-0.22 ± 0.16</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
</tbody>
</table>

* Same data. One-way ANOVA for all +50 D lens groups: \( p < 0.001 \).
oplic errors were observed only if they had also occurred using the single nearer plane condition and these errors were never as great as those that occur in response to similar amounts of defocus in the unrestricted vision situation. While visual information at two planes provides more information to the emmetropisation system than information at just one plane, it was still not as useful as having access to information at a large range of distances.

The information at the additional near plane was provided in two ways, either as a hemi-field with the two halves located at different distances or with a full-field transparent target in front of the further one. While these are different visual treatments, the refractive effects were surprisingly similar, slightly more hyperopia (3 D to 5 D) being produced with the transparent plane compared with comparable hemi-field condition. While this difference may indicate that a half solid target at a near distance has more influence on the refractive error than a transparent one that covers the entire field, it is difficult to make definitive conclusions as the emmetropisation responses to the single planes that comprised these conditions were not always as predicted based on the incident defocus. In addition, the hemi-field target (depending on the defocus levels) produced different eye growth responses in the two halves of the visual field, which would have affected the central refraction and this is unlikely to have occurred with the transparent target.

Regional variations in eye growth have been observed in response to hemi-field occluders. We also measured regional differences with our hemi-field targets. In the situation where half of the eye experienced only low levels of hyperopic defocus and the other half much higher levels (+30 D, hemi-field, -2.81 D and -12.64 D), the half with the greater hyperopic defocus was longer and more myopic. This is further evidence that local mechanisms control eye growth. However, in the case where different levels of myopic defocus were created in each half of the visual field (+50 D, hemi-field, +13.52 D and +20.50 D) no regional differences were measured. We surmise that in this case the high levels of myopic defocus induce a type of form-deprivation myopia and that at the levels used here the amount of myopia induced is not dependent on the amount of myopic defocus applied.

The effect of a transparent target on the emmetropisation response has been compared to the accommodative Mandelbaum effect, where the addition of a competing nearer stimulus results in an accommodation shift towards the nearer target. When transferred to the eye growth system, this effect suggests that the nearer target will result in a myopic shift in the refractive error and increased axial length. We did not observe this effect. In four out of four cases, refractive errors for the transparent condition were more hyperopic than for the corresponding lone further target. This may indicate that this response is not transferable to the eye growth system. Alternatively, differences between these data and those of Wildsoet and Schmid may be due to the anomalous emmetropisation responses observed when the cones are closed with an opaque target.

When information is provided at many distances and hyperopic and myopic defocus are alternated in a temporal fashion, the myopic defocus signal is significantly stronger and, more commonly, hyperopia results. We did not observe a strong bias towards the target with most myopic defocus; instead refractive errors were closer to the target experiencing least defocus. In the situation where low (-2.81 D) and high (-12.64 D) amounts of hyperopic defocus were simultaneously applied in space (+30 D, hemi-field and transparent conditions), the mean refractive errors were -2.53 D and +2.34 D, that is, there was a strong bias away from the high hyperopic defocused target. When myopic (+4.95 D) and hyperopic (-5.89 D) defocus were simultaneously applied (+40 D, hemi-field and transparent conditions), mean errors were -1.61 D and +1.39 D, that is, there was no obvious bias towards either type of defocus. Finally, when low (+1.77 D) and high (+15.52 D) amounts of myopic defocus were simultaneously applied (+50 D, short cone, hemi-field and transparent conditions), mean errors were +2.11 D and +3.05 D and again there was a strong bias away from the high myopic defocused target. These results show that alternations in defocus magnitude in time and space are not comparable manipulations and are dealt with differently by the emmetropisation system.

Our data are consistent with the apparent emmetropisation bias towards distant objects that occurs under normal viewing conditions. This situation is best represented by the +30 D lens treatments, where the further target had -2.81 D of hyperopic defocus (slight accommodation required to view the target clearly, as would occur for distant objects if the viewer were slightly hyperopic) and the nearer target had -12.64 D of hyperopic defocus (much greater accommodation than would be required for a near object). In this situation, induced refractive errors were always more biased towards the further target.

In summary, when visual information is provided at two distances, the target with the least amount of defocus has the greater effect on the resultant refractive error. Emmetropisation responses are more accurate when information is presented at many distances than at just one or even two distances.

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