corneal bearing relationship. The corneal swelling lenses moved about 2 mm, whereas the steeper fitting lenses moved 1 mm or less.

Fig. 2 shows the amount of corneal swelling following 6 hr of wear as a function of the lens–corneal bearing relationship. The corneal swelling ranged from 3.3% to 4.9% and did not correlate highly with the lens–cornea fitting relationship (r = 0.082).

Fig. 3 shows the average tear replenishment rate as a function of lens–cornea bearing relationship. The replenishment rates varied from 1.3% to 2.2% per blink and correlated poorly to the bearing relationship (r = 0.22). With calculations of Fatt and Linn, the oxygen tension contributed by tear pumping for lenses having replenishment rates from 1.3% to 2.2% would range from 1.1 to 2.9 mm Hg.

Discussion. Our results indicate that the lens–cornea bearing relationship of a hydrogel contact lens does not influence the tear replenishment rate or the amount of corneal swelling accompanying lens wear. Although the degree of lens movement could be increased with the use of lenses of longer base curve radius, and thus producing a flatter-fitting relationship, the tear pumping remained unaffected. These data suggest that increasing lens movement (e.g., loosening the fit) by flattening the base curve will not increase the oxygen tension under a lens and therefore will have no effect on reducing the edema caused by corneal hypoxia. These observations are in agreement with earlier studies which have suggested that the central posterior lens radius does not affect the degree of corneal swelling. 1-3

Clinicians often assert that increasing lens movement apparently reduces the degree of corneal edema. Our results do not support this clinical impression. Furthermore, theoretical calculations and experimental measurements of the oxygen transmission for hydrogel lenses show that the oxygen diffusion through most currently worn gel lenses is relatively high. 5, 6 If, additionally, there were significant tear pumping, corneal edema would not be expected to occur, since the oxygen level would be well above the critical level necessary to prevent corneal swelling. 1

The results of this study suggest that corneal edema accompanying hydrogel lens wear must be managed by techniques other than altering base curve radius. Such procedures may include using thinner lenses and/or lenses of higher water content, both of which will increase the oxygen transmissibility of the lens.

Assessment of stereopsis in human infants. SANDRA L. SHEA,* ROBERT FOX, RICHARD N. ASLIN, AND SUSAN T. DUMAIS.

A new method for testing stereopsis in infants is described for use in the early assessment of binocular function. Four 6- and 12-month-old infants were presented with a dynamic random-element stereogram generated on a color television monitor. A stereoscopic form was named laterally, either left or right, to elicit the usual

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attention of the infant. An observer, unaware of the
direction of form movement, made a forced-choice judg-
ment of the direction of form displacement based on
information gleaned from observations of the infant's be-
havior. The observer's performance for all three age
groups exceeded chance levels of responding (p < 0.001). Individual infants within each age group also
provided strong evidence of stereopsis. The applicability
of the method for the screening of binocular anomalies is
discussed.

The development of stereopsis has important
implications for both research on visual develop-
ment and clinical treatment of visual anomalies.
Clinical interest derives from the evidence that
stereopsis is precluded by anomalous conditions
such as strabismus, which impair binocularity.1-4
Clinical tests for stereopsis currently available re-
quire verbal interactions that are unreliable in pa-
tients less than 2½ years of age.5-9 The inability to
test younger patients is an unfortunate limitation
in view of the evidence favoring diagnosis and
therapeutic intervention at earlier ages.10-11

Recently we have described a method of testing
infants for stereopsis in their first postnatal year.12
Our testing procedure is based upon generating a
random-element stereogram in real time on a
modified color video monitor that presents the
stereogram as an anaglyph.13-15 The stereoscopic
form can be moved about in stereoscopic space
without the introduction of monocular cues, and
these movements can be used to engage an infant's
visual attention. If the infant's eye movements and
other attentive behaviors are correlated with the
movement of the stereoscopic form, the infant is
presumed to have the capacity for stereopsis, since
stereopsis is the essential prerequisite for percep-
tion of the stereoscopic form. Using this method,
we have found that stereopsis does not emerge
until the third or fourth postnatal month.

The stereogram generation system used in our
previous study employed a large screen rear-
projection display permanently installed in the
Vanderbilt laboratory. This large display maxi-
mizes the size of the visual field and the extent of
stimulus movement, yet the laboratory installation
limits access to infants drawn from a variety of
populations. To expand the opportunities for test-
ing we devised a more compact stereogram display
system and evaluated its feasibility by testing
three groups of normal infants, ages 4, 6, and 12
months; the two younger groups corresponded to
the ages of infants previously tested, and the 12-
month-old group extended the range by 6 months.

Methods. Infants were solicited by letter and
phone from the birth records in Nashville, Tenn.
Thirty infants provided complete data (at least 10
stereoscopic trials), with 10 infants each at 4
months of age (range 119 to 147 days), 6 months
(range 182 to 198 days), and 12 months (range 340
to 370 days). An additional eight infants did not
complete testing due to excessive fussiness or fail-
ure to tolerate the spectacles (one 6-month-old
and seven 12-month-olds). All infants had a normal
gestation period (37 weeks or more), uneventful
labor and delivery, and acceptable birth weight
(more than 2.5 kg). None of the infants exhibited
any obvious ocular anomalies as judged by lay ob-
servers at the time of testing.

The stereogram generator consisted of a hard-
wired digital logic circuit that modulated the red
and green electron guns of the cathode ray tube of
a 19-inch color television receiver.14-15 Operating
in a raster scan mode, each gun generated a
random-element pattern across the entire video
screen, creating two matrices (red-black and
green-black) with a pixel size of 3.2 mm and total
pixel count of over 12,000.

To introduce retinal disparity, the output of one
electron gun could be delayed for variable periods
of time at any predetermined set of X-Y points
during a scan. The delay produced a different spa-
tial position or gap for a subset of dots in one ma-
trix relative to the corresponding set of dots in the
other matrix, thereby producing the disparity
requisite for stereopsis. The difference in dot po-

cition was camouflaged by filling in the gap with
dots uncorrelated with those within the subsets.
All dots in each matrix were replaced randomly
every 16 msec. The replacement induces apparent
motion of the dots, which resembles the noise
seen on an untuned TV channel. The motion does
not impair the perceptibility of the stereoscopic
form. However, it does eliminate differences in
dot pattern at the boundary of the stereoscopic
form. These differences are present in static ste-
reograms and conceivably could be used as a mon-
ocular cue to stereogram detection. In addition,
the motion permits the stereoscopic form to be
moved along the X, Y, and Z axes without intro-
ducing monocular cues.

To provide the dichoptic stimulation required for
stereoscopic presentation, the display is viewed
through a chromatic filter before each eye. The
filters, one green (Wratten 58) and one red (Wrat-
ten 29), physically route each dot matrix to a sepa-
rate eye. This, of course, is the well-known ana-
glyph method. The color separation provided by
the filters is excellent, and when viewed through
the filters, the display appears devoid of nonste-
reoscopic cues. But to provide a stringent test for
The presence of such cues, experienced adult psychophysical observers attempted to make forced-choice discriminations of the spatial position, left or right, of the stereoscopic form while wearing filters of the same color before both eyes. Even with well-defined trial intervals, feedback, and practice, performance never exceeded chance for either the red or green filters. The apparent motion of the dots seemed particularly effective in camouflaging potential cues because the intrinsic tendency of the perceptual system to impose subjective order upon dynamic random-dot arrays acts as an additional source of noise.

Fig. 1 illustrates the general arrangement used in applying the system to the testing of infants. Each infant was fitted with a pair of wire-rimmed spectacle frames containing one red and one green filter. The infant was held by the parent seated before the television display. At a viewing distance of 36 cm the screen subtended 50 by 60 deg, element size was 30 min, and retinal disparity was held constant at 60 min. The stereoscopic form was an 8 by 12 deg vertically oriented rectangle. The testing room was normally illuminated.

The standing experimenter, concealed from the infant's view by opaque curtains, observed the infant through a peephole (not shown in the figure). The seated experimenter, called the operator, operated the controls of the stereogram generator. The standing experimenter, called the observer, acted in concert with the operator to implement the psychophysical method known as forced-choice preferential looking. The essence of this procedure is that the operator on any given trial or observation period moves the stereoscopic form from the center of the display to the left or right, following a predetermined random order unknown to the observer, and then returns it to screen center. The observer is required to make a forced-choice judgment of the direction of form movement, left or right, based upon observations of the infant's behavior. If the observer's performance differs from chance, it must be due to some behavior of the infant (e.g., eye movements) that is systematically related to the position of the stimulus. Since stereopsis is required for perception of the stimulus, nonchance performance by the observer forces the conclusion that the infant possesses stereopsis. This is the logic of the well-known two-alternative forced-choice method of contemporary psychophysics from which the procedure was derived. It offers the advantages of an objective criterion-free response indicator in lieu of subjective judgments about where an infant appears to be looking.

The testing procedure began with a test of each infant's capacity to attend to the left-right movements of a physical form composed of green dots.

Table 1. Observer's percent correct performance on form movement trials

<table>
<thead>
<tr>
<th>Age group</th>
<th>N</th>
<th>Stereo trials</th>
<th>Physical trials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>S.D.</td>
</tr>
<tr>
<td>4 months</td>
<td>10</td>
<td>71.9</td>
<td>9.8</td>
</tr>
<tr>
<td>6 months</td>
<td>10</td>
<td>76.2</td>
<td>7.4</td>
</tr>
<tr>
<td>12 months</td>
<td>10</td>
<td>77.7</td>
<td>7.3</td>
</tr>
</tbody>
</table>
Table II. Observer's performance for individual infants

<table>
<thead>
<tr>
<th>4 months</th>
<th>6 months</th>
<th>12 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct trials</td>
<td>Total trials</td>
<td>p value</td>
</tr>
<tr>
<td>16</td>
<td>21</td>
<td>0.013</td>
</tr>
<tr>
<td>12</td>
<td>15</td>
<td>0.048</td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>0.021</td>
</tr>
<tr>
<td>11</td>
<td>14</td>
<td>0.029</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>0.038</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>0.055</td>
</tr>
<tr>
<td>9</td>
<td>12</td>
<td>0.073</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
<td>0.090</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>0.407</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>0.500</td>
</tr>
</tbody>
</table>

*Performances have been ordered by ascending p value within each age group. p values are based upon the binomial test.

against a black background. This physical form was of the same dimensions and configuration as the stereoscopic form. As specified by the forced-choice procedure just described, the observer was required to judge the position of the form by observing the infant's behavior. Performance of at least 66% correct was the predetermined prerequisite for admission to the stereoscopic portion of the test. Of those infants successfully meeting this criterion, only one required six trials with the physical stimulus, two required five, and the remainder passed at four. Of the seven infants who did not meet the criterion, one 4-month-old was rejected because of extreme fussiness, and six 12-month-olds refused to tolerate the wearing of spectacle frames.

As soon as the physical-form criterion was met, the test for stereopsis was initiated by switching to the stereoscopic form. The predetermined minimum number of trials was 10; beyond that, trials were administered until the infant became fussy and inattentive or until the predetermined maximum of 20 trials was attained. Upon completion of the stereoscopic trials, four trials with the physical form were administered to provide some basis for inferring the infant's reactive state during the stereoscopic trials. Successful performance on the physical trials would suggest that the infant had not developed a general disdain for the testing situation that would have inhibited interest in both physical and stereoscopic stimuli. All infants, however, did perform successfully on this second series of physical form trials. The switch of the display from the stereoscopic mode to the physical mode seemed to restore the infants' interest and attention.

The procedure followed in administering each trial, both physical and stereoscopic, probably served to underestimate performance. A trial began when the infant appeared to be oriented toward the center of the display. At this point the observer would signal the operator, who moved the form 20 deg left or right and then returned it to the center position. The rate of movement was approximately 10 deg/sec. The observer made an immediate decision about the direction of form movement and received immediate feedback from the operator. On some trials an infant would appear to look away from the center of the display just before the operator started movement of the form. If the direction of form movement was at odds with the observer's judgment of the infant's attentional response, then performance would be impaired. Such trials, however, were not excluded except for a few obvious cases, and their inclusion in the data analysis contributes to an underestimation of performance. A second contributing factor is that the return of the form to the center, coupled with the immediate decision of the observer, tended to vitiate the performance of infants who responded slowly. On the other hand, the trial procedure did reduce the time required for testing. Starting at the point where the spectacles were put on the infant, testing time ranged from 5 to 15 min, depending on the attentiveness of the infant and the number of trials administered.

Results. The performance of infants in the three age groups is summarized in Table I. The mean level of correct responding on stereoscopic-form trials was above 70% and exceeded chance levels in all groups (p < 0.001). It is also of interest to consider the performance of individual infants. Table II presents the observer's performance for individual infants on stereoscopic-form trials. The binomial test was used to estimate whether or not
the performance for each infant was above chance. Note that within each age group at least one half of the infants performed at the 0.05 level or better. Given that a minimum of only 10 trials was required from each infant and the fact that the scoring procedure was relatively conservative, one might also consider the performance in the 0.05 to 0.10 range to provide acceptable evidence of stereopsis. However, five infants (two at 4 months, two at 6 months, and one at 12 months) performed more poorly than the 0.10 level. These infants may in fact have an impaired capacity for stereopsis. But their poorer performance could be due to a variety of factors, and additional testing would be required to establish unequivocally that a deficit in stereopsis was present.

Discussion. The results of the present study are fully consistent with those of our earlier study,13 which indicated that stereopsis becomes functional no earlier than about 3½ months of age. It should be noted, however, that such estimates are based on the average performance of groups of infants. For individual infants the time of emergence of stereopsis varies considerably. We have tested one infant who gave reliable evidence of stereopsis at an age of 2½ months (77 days).

The present results also suggest that the smaller, more compact stereogram display system is at least as effective as the larger laboratory system. Indeed, our impression is that the smaller system offers some intrinsic advantages. First, the higher luminance of the display relative to a projection TV system attracts attention and makes ambient illumination a less critical parameter. Second, the viewing position of the experimenter permits closer scrutiny of the infant's eyes and face, thus making it easier to judge attentional responses. These advantages reduce the time required for testing and, in concert with the portability of the system, should facilitate the acquisition of normative data in field settings and the repeated testing of individuals before and after therapeutic intervention.

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Key words: stereopsis, dynamic random-element stereogram, human infants, strabismus, amblyopia

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