Pupillary Measures of Binocular Luminance Summation in Infants and Stereoblind Adults

Sandra L. Shea,* Jane A. Doussard-Roosevelt, and Richard N. Aslin*

Preverbal infants and children with ocular misalignments do not perform well on standard clinical measures of binocular function which require accurate alignment of the eyes. In 1983, Birch and Held described a pupillary measure of binocular luminance summation that could be used to assess binocular function in strabismic infants. They reported a correlation between the onset age of stereopsis and the onset age of binocular luminance summation, with both emerging at the end of the fourth postnatal month. Using a similar pupillary technique, we measured significant levels of binocular luminance summation in infants as young as 2 mo of age, as well as in stereoblind adults. In addition, the infant's pupillary system, in comparison to the adult's, showed reduced magnitudes and increased latencies to luminance increments. The sensitivity of the pupillary system to luminance increments provided a better predictor of binocular luminance summation (Pearson r = 0.88) than did stereoscopic performance (Pearson r = 0.43). These data suggest that developmental changes in the pupillary system itself, rather than factors intrinsic to binocular vision, may have been the source of the correlation between binocular luminance summation and stereopsis reported by Birch and Held.


Birch and Held1 recently described a measure of binocular luminance summation whose developmental onset was highly correlated with the onset age of stereopsis in human infants. They reported that as stereopsis emerges between the third and fifth postnatal months in normal infants, the presence of binocular luminance summation becomes evident and follows a similar developmental time course. The essential feature of binocular summation is that inputs delivered to the two eyes are integrated to yield a binocular signal that is greater than either monocular component, and the level of integration exceeds that predicted by probability summation (see reviews by Blake and Fox2 and Blake, Sloane, and Fox3). If binocular luminance summation is present, then the integrated luminance signal will be larger if both eyes view an even-luminance stimulus field than if one eye views the field and the other is patched. Birch and Held’s measure of binocular luminance summation employed the pupillary constriction that follows a shift from monocular to binocular viewing conditions. That is, removal of the patch from one eye increases the integrated luminance signal and leads to a steady state constriction in the unpatched eye, even though no luminance increment was delivered directly to the unpatched eye.

Birch and Held1 reported that stereonormal adults and infants older than 4 mo who have stereopsis show binocular luminance summation consisting of a pupillary constriction of approximately 15–20% in the unpatched eye. Infants under 4 mo of age who do not have stereopsis did not show significant levels of binocular luminance summation using their pupillary technique. Based in part on a report that stereoblind adults also fail to show binocular luminance summation,4 Birch and Held1 concluded that “the visual pathways by which signals from the two eyes converge are not functional until the fourth month of life.”

Given the correspondence between the onset ages for stereopsis and binocular luminance summation, as well as other evidence for the absence of binocular summation in stereoblind adults,5,6 Birch and Held1 concluded that their pupillary technique “may be particularly suitable for use in testing strabismic infants. It requires a minimum of time and cooperation from the infant and can assess the integrity of binocular visual pathways even in the presence of large angle tropias.” What remains unclear from the data presented by Birch and Held1 is whether stereopsis and binocular luminance summation are me-
diated by the same neural mechanism. Although bi-
nocular summation for contrast threshold and in-
crement detection tasks has been attributed to
cortical binocularity, it is not clear that the pupillary
system employs cortical mechanisms to mediate bi-
ocular luminance summation.

The purpose of the first experiment, therefore, was
to determine if Birch and Held were correct in
concluding that binocular luminance summation is
absent in infants prior to the fourth postnatal month
and to determine if ten Doesschate and Alpern were
correct in concluding that stereoblind adults fail to
show binocular luminance summation. This latter
goal was particularly important because ten Doess-
chate and Alpern tested only two stereoblind adults.
If the onset age for binocular luminance summation
is earlier than 4 mo, and if stereoblind adults show
significant levels of binocular luminance summation,
than it is likely that binocular luminance summation
as assessed by pupillometry is mediated by some
neural mechanism other than the binocular cortical
neurons subserving stereopsis.

Materials and Methods

Experiment 1

Subjects: Twenty stereonormal college students and
26 students with a history of ocular disorders were
recruited for testing. Six of the subjects with an
abnormal ocular history were dropped from the study
because they did not meet our criteria of having had
strabismus, amblyopia, and/or patching therapy dur-
ing some period of childhood. The TNO stereoacuity
test and a dynamic random-element stereogram test
were administered to all 40 subjects. Our criteria for
stereoblindness consisted of a failure to have stereo-
acuity of 120 arc sec or better on the TNO and a
failure to provide above-chance detection of the dy-
namic random-element stereogram. Eleven of the 20
subjects with an abnormal ocular history met the
criteria of stereoblindness, with a mean TNO score
of 436 arc sec and a mean of 55% correct on the
dynamic random-element stereogram. The nine sub-
jects who did not meet the criteria for stereoblindness
had a mean level of stereacuity on the TNO of 58
arc sec as compared to the mean of 24 arc sec shown
by the 20 stereonormal adults. Similarly, these nine
adults with an abnormal ocular history but some
stereopsis detected the dynamic random-element ste-
reogram on an average of 93% of the trials in com-
parison to the mean percent correct of 99 shown by
the stereonormal adults. Finally, 10 infants between
the ages of 65 and 98 days (9-14 wk) were also tested
for binocular luminance summation. This age range
was selected because Birch and Held found that
stereopsis emerged at an average age of 15.5 wk and
binocular luminance summation emerged at an av-
erage age of 15.8-16.1 wk. Informed consent was
obtained from all adult subjects, or parents of infants,
prior to data collection.

Apparatus and procedure: An Applied Science Lab-
oratories Model 1994 eye monitoring and pupillo-
metry system was used to record the size of the right
pupil while the left eye was occluded with an opaque
patch. The pupillometer consisted of an infrared-
sensitive television camera that viewed the eye through
a large beam splitter. An infrared-filtered light source,
collimated and aligned coaxially with the camera
lens, created a fundus reflex and its resultant bright
pupil. The image of this bright pupil was analyzed
by analog and digital circuitry that counted the
number of scan lines from the top edge to the bottom
edge of the pupil. Because the vast majority of infant
eye movements are along the horizontal axis, par-
allax errors in the measurement of pupil size were
minimized. Pupil size was measured with a resolution
of 0.01 mm, sampled at a rate of 60 Hz, and stored
on computer disk for later analysis.

Infants were tested while seated in the lap of an
adult holder who kept the infant's right eye in the
camera's field of view with feedback from a small
television monitor. This monitor also enabled the
holder to maintain the infant's pupil in optimum
focus. The adult subjects were positioned in a chinrest
so that their right eye was in the same location as the
infant's. Each subject was light-adapted for 4 min
while viewing the image of a large television screen
(45° X 50°) reflected from the beam splitter. Screen
luminance was 1.96 cd/m² as in the Birch and Held
study. During the second 2 min of adaptation, pupil
size data were collected continuously in the infants
in 5-sec segments, whereas in the adults, 5-sec seg-
ments of data collection were alternated with 5-sec
rest periods to allow for voluntary blinks. After
adaptation, the patch was removed and data were
collected for an additional 2-min period following
the procedures used during adaptation. Only the data
from the last minute of binocular viewing following
patch removal were used in the computation of
binocular luminance summation because Birch and
Held estimated at least 20-30 sec were required for
the pupil to reach a steady state. Although screen
luminance was the same as in the Birch and Held
study, screen size was smaller (45° X 50°, as compared
to the entire visual field). However, ten Doesschate
and Alpern obtained evidence of binocular luminance
summation with pupillometry using a 12-deg field.
We also could not replicate exactly the timing of data
was computed with a software algorithm. If blinks or large fluctuations (more than 1 mm) were present in the segment, the average of all 300 samples for that segment of data were not scored. If no artifact-free section longer than 1 sec was present, the data from that 5-sec segment were not scored.

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The experiment was divided into two groups: a younger group, ranging in age from 73 to 98 days, and an older group, ranging in age from 117 to 190 days. These age groups were chosen to precede and succeed the onset age for stereopsis and binocular luminance summation reported by Birch and Held. The adults were either emmetropic (1) or corrected myopes (2), and ranged in age from 22 to 34 yr. Informed consent was obtained from all adult subjects, or parents of infants, prior to data collection.

Apparatus and procedure: The apparatus used to record changes in pupil size and to present the stimuli was identical to that used in experiment 1. The stimulus consisted of a large television screen (45° X 50°) with an even background luminance of 1.96 cd/m². This background luminance was selected to determine how luminance increments affected pupillary responsiveness at the same level of light adaptation used in experiment 1. Luminance increments to the entire screen were 0.1, 0.3, 0.5, and 0.7 log units above the background. Each increment was 500 msec in duration and was separated by at least 5 sec to allow the pupil to return to a steady state. Trials on which the eye monitoring system indicated the infant to be fixating off screen were eliminated from further analysis. All subjects were tested monocularly with an opaque patch covering the left eye.

Results

Experiment 1

Figure 1 illustrates the pupillary constriction in the unpatched eye that occurred in the test of binocular luminance summation for each of the three groups of adults and for the group of infants. Note that three different scoring criteria were used: (1) the metric used by Birch and Held, consisting of the difference in pupil diameter expressed as a percentage of iris diameter; (2) the percentage decrease in pupil diameter; and (3) the percentage decrease in pupil area. The first scoring metric was used for comparison to Birch and Held's data. We used a constant iris diameter of 10 mm to compute this difference score because our pupillometer did not provide an automated measure of iris size. This constant value for iris diameter was based on measures taken directly from the video image of the pupillometer for selected subjects. The second and third scoring metrics were used to provide a relative measure of pupillary constriction. The area metric is perhaps most relevant because it corresponds to the change in the amount of light actually reaching the retina. All three groups of adults show clear evidence of binocular luminance summation regardless of the scoring metric. Individual t-tests on each subject's scores indicated that two of the 11 stereoblind adults failed to show reliable evidence of summation, as did one of the 20 normal adults. The magnitude of summation did not differ significantly between the normal and abnormal groups, but the normal and stereoblind groups did

![Figure 1](https://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933124/ on 12/09/2018)
differ at the 0.05 level.* The Pearson correlation between the magnitude of summation and the TNO measure of stereoaucity (sec of arc) was −0.41. The Pearson correlation between the magnitude of summation and percent correct on the dynamic random-element test of stereopsis was 0.43. Both correlations were moderate but significantly different from zero (P < 0.01). Finally, the mean summation magnitude of the infant group, while smaller than any of the adult groups, was significantly greater than zero (P < 0.05).

The results from this first experiment indicate that stereoblind adults show significant levels of binocular luminance summation as assessed with a pupillary technique. In addition, the magnitude of binocular luminance summation correlates only marginally with the level of stereoacuity, accounting for approximately 20% of the variance in the two measures. The discrepancy between these findings and those of ten Doesschate and Alpern4 may be explained by considering two possibilities. First, it is possible that the stereoblind adults tested in experiment 1 did not lose binocular neurons during an early period of binocular deprivation, but rather lost the ability to perceive depth in stereograms at some later age. Some essentially nonbinocular factors such as anisometropia can degrade stereoscopic performance11,12 despite an intact neural mechanism for stereopsis. Without more complete information on their medical histories, this explanation cannot be ruled out. A test of this hypothesis would entail measurements of binocular luminance summation in congenital strabismics who have been deprived of normal binocular vision for many years and have presumably lost all cortical binocularity. It is possible that the two strabismics tested by ten Doesschate and Alpern4 had an ocular deviation beginning early in childhood or suffered from a congenital binocular deficit.

A second possibility is that binocular luminance summation does not share the same neural mechanism as the disparity detection required of stereopsis. This possibility is consistent with the results of the current experiment as well as corroborating anatomical evidence. The afferent pathways from the two retinas converge on nuclei in the brainstem.13,14 Thus, although there may be an additional cortical influence on binocular pupillary activity, this cortical influence is unlikely to be a necessary requirement for the presence of binocular luminance summation.

The results from this first experiment also indicate that infants younger than the reported age of onset for stereopsis show significant levels of binocular luminance summation. This discrepancy between our results and those reported by Birch and Held1 may be explained by the greater resolution of the pupillometer used in the present study. Although both studies reported mean binocular luminance summation in 9- to 14-week-olds of approximately 2–3%, the pupillary measures in the present study were apparently less variable, thereby yielding above-chance performance.

What remains unclear from these results is the explanation for the greatly diminished level of binocular luminance summation in young infants compared to the levels in both normal and stereoblind adults. Because the essential feature of the pupillary measure of binocular luminance summation used by Birch and Held and in experiment 1 is a luminance increment delivered to the previously patched eye, it is possible that the diminished responsiveness of the developing pupillary system itself may account for the reduced magnitude of pupillary constriction seen in these measures of binocular luminance summation.

To test this possibility, the sensitivity of the pupillary system to luminance increments was examined in the next experiment.

**Experiment 2**

The mean magnitudes of pupillary constriction to the four luminance increments are shown in Figure 2A for the two infant groups and the adult group. No infant showed a constriction to the 0.1 log unit increment, and except for the largest increment, infant response magnitudes were smaller than adult response magnitudes. Figure 2B presents the proportion of trials on which infants and adults showed a measurable constriction. The likelihood of a constriction was greatly diminished in infants compared to adults, except for the largest increment.†

These results indicated a marked difference between the infant and the adult pupillary response to luminance increments: it is also interesting to note that the mean latency to pupillary constriction was 508 msec in the younger group of infants and 440 msec in the older group of infants, compared to 352 msec in the adults. A similar increased latency of pupillary constriction has been reported in the ambyopic eyes of human adults.15

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* Any technique used to assess the performance of individual subjects (eg, in a clinical setting) must be successful at correctly diagnosing normals as normals and abnormals as abnormals without incorrectly diagnosing normals as abnormals or abnormals as normals. Although the mean level of binocular luminance summation in the group of stereoblind subjects was significantly less than in the group of normals, the range of scores in the two groups was nearly identical (summation scores ranged from 13 to 38% for the stereoblinds and from 18 to 65% for the normals). Thus, binocular luminance summation does not appear to differentiate between subjects along the important clinical dimension of stereoacuity. However, binocular luminance summation may, in some cases, provide useful clinical information about some aspects of binocular functioning.

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nance increments. Therefore, we reexamined the results from experiment 1 by calculating the magnitude of pupillary constriction that occurred in the unpatched eye immediately after patch removal rather than after a 1-min delay. As shown in Figure 3, the initial pupillary constriction after patch removal in infants is significantly less than in adults \((P < 0.001)\), and the constriction in stereoblind adults is somewhat less than in normal adults. The similarity in the data shown in Figures 1 and 3 indicated that the magnitudes of initial pupillary constriction and of binocular luminance summation are closely related. The Pearson correlation across all 40 adults and 10 infants between the magnitude of the initial pupillary constriction after patch removal and the magnitude of binocular luminance summation was 0.88 \((P < 0.001)\).

Figure 4 illustrates the mean pupillary response after patch removal for three infants and four normal adults from experiment 1. It is apparent that the magnitude of the initial constriction in the infants is less than in the adults, and the infant pupil returns to a steady state sooner than the adult pupil. Because the data on binocular luminance summation were collected at a constant time interval after patch removal in these two groups of subjects, and because the magnitude of initial pupillary constriction was greater in adults than in infants, the measures of pupillary constriction used as an estimate of binocular luminance summation are clearly greater in adults than in infants.

**General Discussion**

The data from experiment 1 indicate that stereoblind adults show significant levels of binocular luminance summation as assessed by a pupillary technique very similar to that used by Birch and Held. In addition, normal human infants younger than Birch and Held's reported age of onset for either stereopsis or binocular luminance summation showed significant levels of binocular luminance summation. These findings, along with the moderate correlations between stereopsis and binocular luminance summation, imply that the pupillary measure of binocular luminance summation is not mediated by the same neural mechanism that underlies stereopsis. Thus, Birch and Held's contention that binocular luminance summation “... may be particularly suitable for use...” is not supported by these findings.
in testing strabismic infants" is relevant only to an aspect of binocularity weakly related to the cortical mechanism subserving stereopsis. For example, as suggested by Alpern, 16 the pupillary system may provide a global index of the suppression observed under conditions of binocular rivalry. Only further tests of binocular luminance summation using this pupillary technique in infants and younger children with known or suspected binocular anomalies will determine if this measure serves a useful clinical function.

The data from experiment 2 indicate that the infant pupillary system is much less sensitive to luminance increments than the adult pupillary system. Because the pupillary system is essentially consensual, this monocular increment results in a transient or phasic constriction of the pupil in the unpatched eye. A reexamination of this initial pupillary constriction after patch removal in experiment 1 revealed a reduced constriction in infants compared to adults. Moreover, the magnitude of this initial pupillary constriction correlated very highly with the magnitude of binocular luminance summation.

If the initial pupillary constriction in the light-adapted eye following the removal of the patch from the nonviewing eye had been equal in infants and adults, then the absence of binocular luminance summation would have indicated an uncoupling of the luminance signals from the two eyes. However, the magnitude of the initial pupillary constriction after patch removal was considerably less in infants than in adults. Thus, the “effective” luminance increment used to assess the magnitude of binocular luminance summation was not equated in the two age groups. One possible explanation of the reduced pupillary constriction in young infants is the diminished pupillary sensitivity to luminance increments demonstrated in experiment 2. Another possible explanation is that infants may undergo periods of monocular suppression in the presence of interocular luminance differences. This possible monocular suppression is supported by the data in Figure 2B showing that on some trials there was no measurable pupillary constriction to luminance increments that on other trials elicited clear constrictions. Whether these or other explanations best account for young infants’ reduced magnitudes of pupillary constriction following patch removal, the very high correlation between initial pupillary constriction and the magnitude of binocular luminance summation suggests that this pupillary measure may not be a valid indicator of binocular function per se. Rather, developmental differences in the pupillary measure of binocular luminance summation may more closely reflect an increasing sensitivity of the visual system to changes in luminance.‡

‡ Similar data on binocular luminance summation using the pupillary response have recently been collected in the cat by R. Sireteanu and L. Altmann (personal communication). They showed that binocular luminance summation was of reduced magnitude in two of three strabismic cats and in 27 normal 2- to 10-week-old kittens. They also showed that pupillary responsiveness was correlated with the magnitude of binocular luminance summation.
Key words: binocular summation, pupillometry, stereopsis, infants

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