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"Vernier Acuity is Less Than Grating Acuity in 2- and 3-Month-Olds"

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VERNIER ACUITY IS LESS THAN GRATING ACUITY IN 2- AND 3-MONTH-OLDS

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Abstract—Vernier acuity and grating acuity were measured longitudinally starting at 1 or 2 months of age in 22 infants, using a two-alternative, forced-choice preferential looking technique. For vernier acuity, the motion-sound display was employed. For grating acuity, a preferential looking method was employed. Steps of the stimulus (vernier offset and spatial frequency of the grating) and procedures were basically identical between the two acuity tests. The range of stimuli was set so as to compare the two acuities at younger ages. Results show: (1) vernier acuity is less than grating acuity at 11–12 weeks of age or younger, and (2) the developmental rate of vernier acuity is greater than that of grating acuity in the first half-year of life. To interpret the data, it was speculated that: (1) the mean sampling distance (center-to-center distance between receptive fields) may influence vernier acuity more than grating acuity, whereas the size of the receptive field may influence grating acuity more than vernier acuity: (2) when the mean sampling distance is large relative to the size of the receptive field, vernier acuity may be less than grating acuity. Thus, the neonatal visual system, just as the visual system in the periphery and in strabismic amblyopia, may be characterized by spatial undersampling.

Infants Vernier acuity Grating acuity Hyperacuity Preferential looking Receptive field Spatial sampling

INTRODUCTION

Grating acuity is defined as the highest spatial frequency of high-contrast grating that can be resolved. In the case of infants, more specifically, the behavioral definition refers to the minimum angular separation between the edges of a grating stimulus which the infant can barely discriminate from an otherwise equivalent homogeneous gray stimulus (Fantz and Ordy, 1959; Salapatek *et al.*, 1976; Teller *et al.*, 1974; Gwiazda *et al.*, 1978). The development of grating acuity of infants younger than 12 months of age has been assessed by the preferential looking technique (for review, see Dobson and Teller, 1978; Held, 1979; Gwiazda *et al.*, 1980). It is characterized by a continuing development through the first year of life and beyond. According to data obtained by the two-alternative, forced-choice version of the method (Gwiazda *et al.*, 1980), grating acuity reaches 1.5 c/deg by 2 months, 3.0 c/deg by 4 months, 6 c/deg by 7 months, and 12.0 c/deg by 12 months of age.

Vernier acuity, the inverse of the smallest detectable misalignment of edges, is a type of hyperacuity (Westheimer, 1979) which may be considered an outcome of central visual processing. In the normal adult, it is higher than grating acuity by almost an order of magnitude (Westheimer 1979). Shimojo *et al.* (1984) compared grating and vernier acuities cross-sectionally in infants aged from 2 to 9 months. The conventional two-alternative, forced-choice preferential looking method was employed to measure grating acuity. Vernier acuity was measured by a newly developed motion-sound display. In this display, a pair of striped patterns was presented, one of which contained horizontal vernier offsets on its edges. The displacement of vernier offsets gave the impression of intermittent motion of a target which was defined by these offsets. The motion was perceived only when the vernier offsets were detected, and was synchronized with beeping sounds [for details, see the "Apparatus and stimuli" section, and

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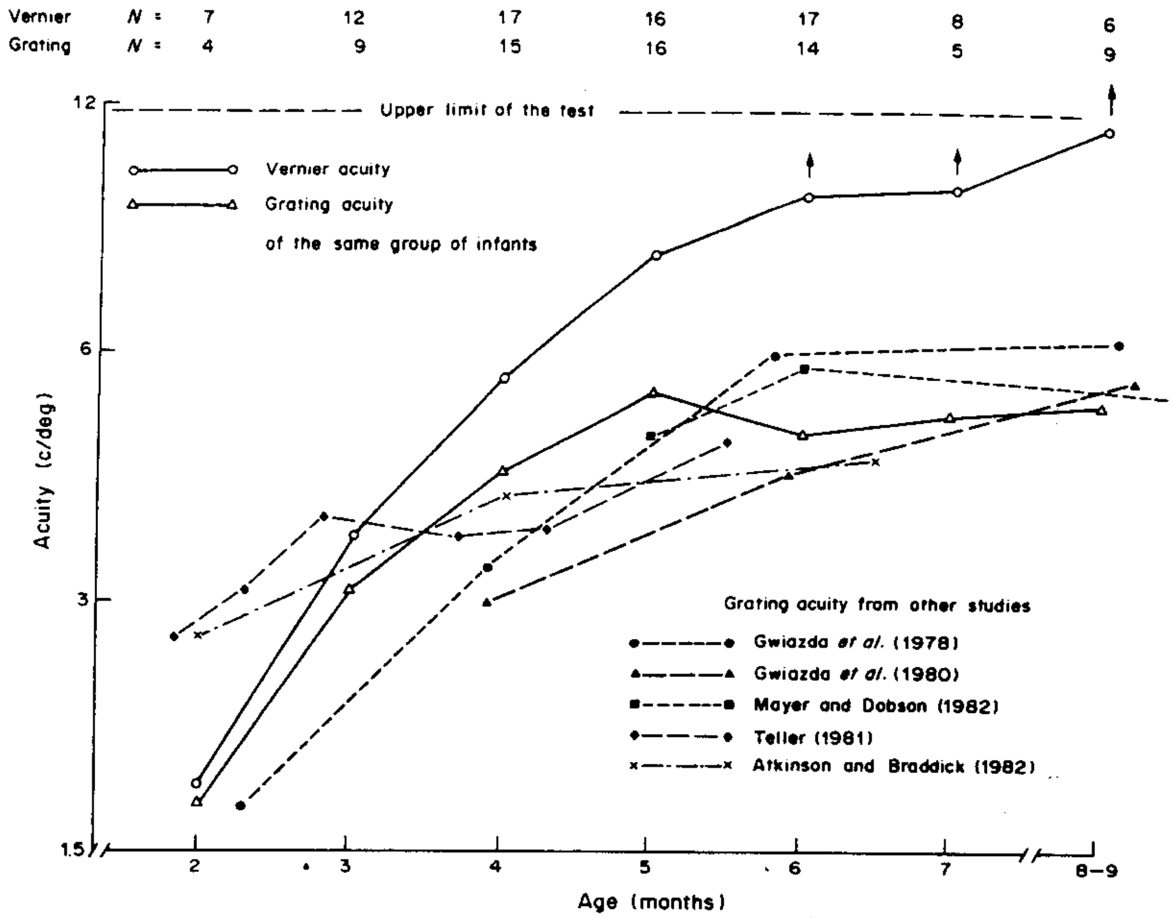

Fig. 1. Development of vernier and grating acuity (taken from Shimojo *et al.*, 1984). Log acuities (c/deg) are plotted as a function of age (months). Open circles: vernier acuity (expressed in the spatial frequency of stripes which have a bar width equivalent to the threshold vernier offset). Open triangles: grating acuity. Dotted lines: grating acuities taken from other behavioral studies.

also Figs 1 and 2 in Shimojo *et al.* (1984)]*. Vernier acuity was found to be superior to grating acuity only at and after 4 months of age [Fig. 1; taken from Shimojo *et al.* (1984)]. We tacitly assumed that vernier acuity would not be less than grating acuity before that age and speculated that underlying cortical changes at that age serve as a physiological basis for achieving hyperacuity.

In the previous study, the range of spatial frequency of the square wave grating was 0.75 c/deg (40 min of arc in terms of bar width) to 12 c/deg (2.5 min). The Upper (larger) limit of the vernier offset of the display was fairly small (19 min) in accord with our above-mentioned assumption. Larger offsets were sacrificed in order to keep the lower limit small enough (2.5 min) to test older infants. If the infant failed to reach criterion preference even at the largest offset (19 min), that largest value was used arbitrarily as the estimated vernier acuity of the infant. For this reason, there was an ambiguity in the interpretation of the data particularly at the youngest ages (2–3 months). Is vernier acuity literally equal to grating acuity at these ages? If so, is it either grating acuity [Fig. 2(B)] or vernier acuity [Fig. 2(C)] that changes its developmental rate at 4 months of age? Or instead, would it not be more plausible that the developmental rates of the two acuities are constant, and that the difference between them was simply too small to stand out from the noise at the earlier ages [Fig. 2(A)]? As the fourth possibility, now questioning our previously tacit assumption, it might even be conceivable that vernier acuity can be less than grating acuity at these young ages [Fig. 2(D)]. In this case, there should be a crosspoint at 3–4 months of age. If the data are actually like Fig. 2(B) or (C), they may suggest that the same underlying neuronal

*Although the visual task here is not totally identical to the typical task of vernier acuity, adult observers showed values which were comparable to the range of vernier acuity obtained with more conventional methods (Shimojo *et al.*, 1984).

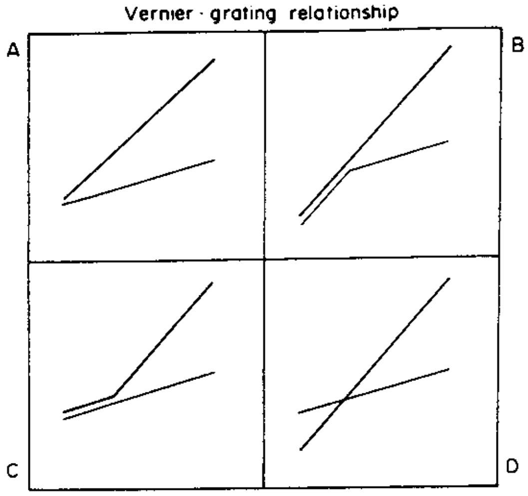

Fig. 2. Vernier-grating relationship. Four possibilities (A–D) of developmental profile are illustrated here. Thick lines: vernier acuity. Thin lines: grating acuity.

mechanism determines both vernier and grating resolution during the early period, but different mechanisms constrain the developmental rates of the two acuities after 4 months of age. If the data appear more like Fig. 2(A) or (D), they may suggest that different underlying mechanisms are responsible for the developmental rate of the two acuities during the period. Even though it may appear counter-intuitive, there is some reason to expect the fourth case [Fig. 2(D)] as a possibility, as detailed in the following. And in fact, some data supporting this idea will now be presented.

The grating acuity task requires discrimination of a striped pattern from a homogeneous gray field. The highest resolvable spatial frequency, i.e. grating acuity, may depend on the smallest size (and contrast sensitivity) of receptive field that shows functionally effective contrast sensitivity at the age (Atkinson *et al.*, 1974; Banks and Salapatek, 1978). On the other hand, the vernier acuity task requires detection of offsets in striped patterns. Note that in this vernier task, the spatial frequency of the target (the indented part of the stripes) is the same as the background. Therefore, it is in fact a task requiring detection of a phase shift of square wave gratings. Phase shift detection, i.e. vernier acuity, may depend more on the density of receptive fields than on the size of them. In other words, when the mean sampling distance is larger (the density of receptive fields is lower), vernier acuity would be degraded more than grating acuity. (All of these discussions are limited to the peripheral levels of visual processing. The central processes should be important particularly for vernier acuity.) To support this idea, Hirsch and Hylton (1982) and Wilson and Gelb (1984) independently found in their studies on spatial frequency discrimination that the mean distance between two receptive fields (Wilson and Gelb) or sampling lattice (Hirsch and Hylton) determines the accuracy of positional information*. Thus, if the size and density of receptive fields have different developmental profiles, and affect the two acuities either independently or at least differently, then independent developmental rates of the two acuities would be expected [Fig. 2(A)]. Furthermore, when the density of receptive fields is extremely low relative to their size, vernier acuity would be less than grating acuity [Fig. 2(D)]. Based on essentially the same idea, Levi and Klein (1985) recently explain the quick elevation of vernier threshold relative to grating threshold as a function of eccentricity in strabismic amblyopes (will be detailed in the Discussion).

To illustrate this point, compare Fig. 3(A) and (B). These are hypothetical receptive field structures. For a simplification, the receptive field size is kept constant in the two cases. Therefore, the expected grating acuity would be the same between these two cases, as long as the size of the striped stimulus is large enough to cover a sufficient number of receptive fields. The distance between two receptive fields is much larger than the size of them in Fig. 3(A), but is about the same as the size of them in Fig. 3(B). As is obvious in Fig. 3(A), the vernier threshold would be much larger than the receptive field size, or the grating threshold in this case. In the case of Fig. 3(B), on the contrary, the vernier threshold should be at least the same as grating acuity. [To be realistic, we should also consider the central "interpolation factor" (e.g. Hirsch and Hylton, 1985) which significantly and selectively improves vernier acuity, but we neglect this for simplicity.] Furthermore, when there is uncertainty in the orientation of edges [see Fig. 3(A) and (B)], the undersampling (larger sampling distances) may further degrade phase shift detection but not grating acuity. Thus, if the receptive field structure at very young ages is characterized by a low effective density of receptive fields as illustrated in Fig. 3(A) the density

*Recently, Wilson (1986) proposed a more explicit mathematical model which can well predict the human performance in various sorts of hyperacuity task.

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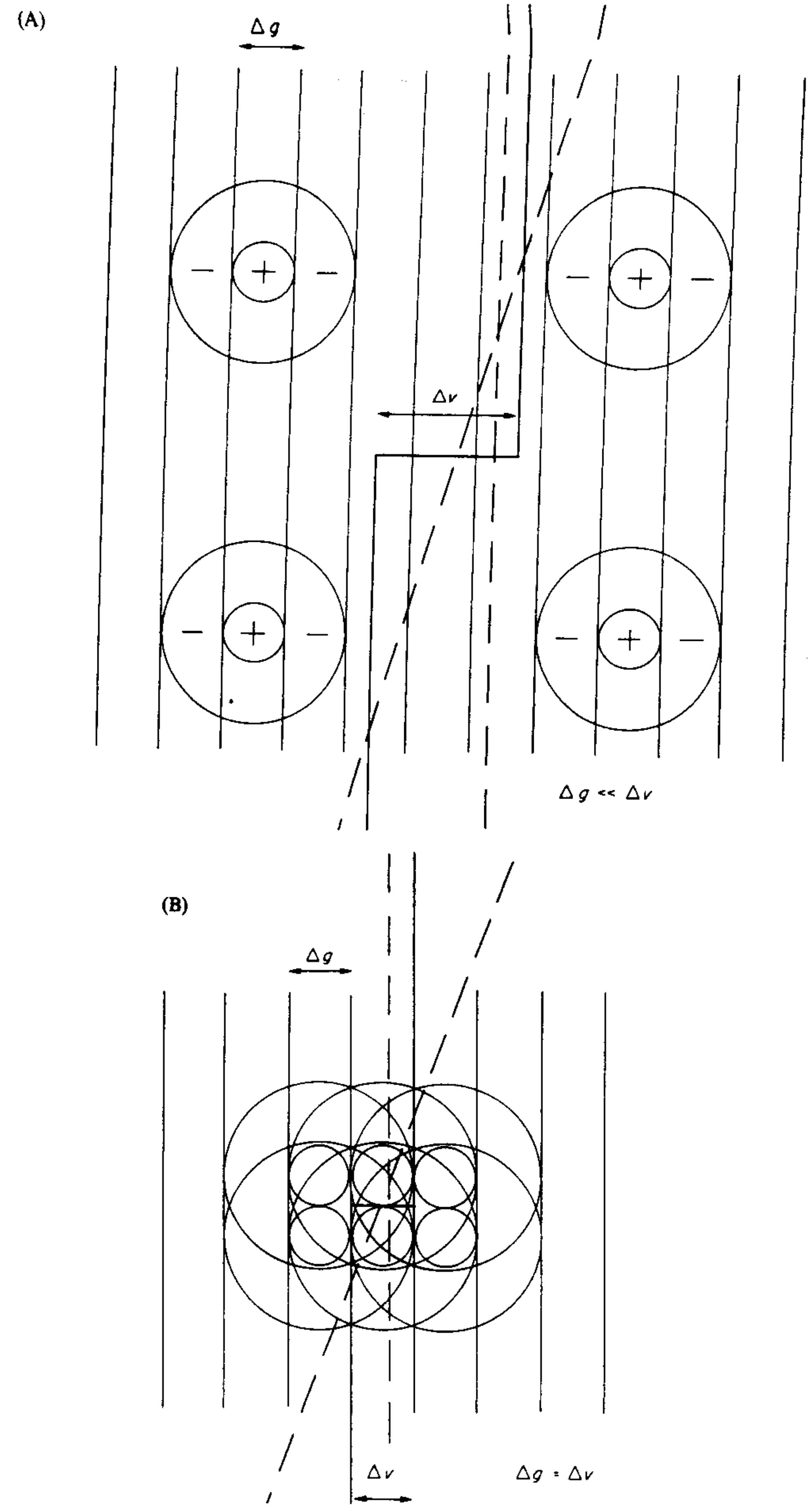

Fig. 3. Hypothetical relationship between receptive field size and spatial sampling. (A) Neonatal: averaged spatial sampling is coarser than the size of receptive field. (B) Mature: average spatial sampling is roughly equal to the size of excitatory receptive field.

4.

increases faster than the size of receptive fields with increasing age, then both a lower initial value and a faster developmental rate of vernier acuity as illustrated in Fig. 2(D) would be expected. We now report data that are consistent with this prediction. The anatomical and physiological plausibility of the abovementioned speculation about the underlying mechanism will be discussed later (Discussion).

METHODS

Subjects

Twenty-two infants (7 females, 15 males) aged 7–15 weeks were tested. Eighteen of them (6 females, 12 males) finished the 8 visits that were originally scheduled. The other (4) infants, who did not finish for practical reasons, were included in the cross-sectional data analysis, but excluded from the longitudinal data analysis.

Apparatus and stimuli

The apparatus and stimuli were the same as used in the previous study (Shimojo *et al.*, 1984) except that in the vernier test, the distance from the infant to the display was 47 cm (80 cm in the previous study) so that the 5 steps of vernier offset (40, 20, 10, 5 and 2.5 min arc) were identical with the 5 steps of stripe width in the grating acuity test.

1. Vernier acuity test: a pair of striped patterns was presented on the monitor of a TERAK computer. The whole stimulus area subtended 23.3 deg (horizontal) × 18.8 deg (vertical) of visual angle at the observation distance of 47 cm. Each of the high contrast (0.80) striped patterns was 8.3 deg wide and 18.8 deg high. Their centers were separated by 15.0 deg. One of them contained a set of horizontal vernier offsets on its edges, which were displaced vertically along the edges in time with synchronized beeping sounds. The spatial frequency of the stripes was fixed at 0.65 c/deg (46 min arc for each stripe), the size of the target framed by the vernier offsets was fixed at 8.3 deg (H) × 4.7 deg (V), and the range of its vertical displacement was also fixed at 1.5 deg. The displacement was at a rate of 0.75 c/sec.

2. Grating acuity test: the apparatus and stimuli described in detail previously (Gwiazda *et al.*, 1980) was used. Briefly, it consisted of a wooden partition containing two circular translucent screens, one to the right and one to the left of a red fixation light. A small peephole was located below the fixation light. Each screen subtended 11 deg of visual angle with centers separated by 36 deg at the observation distance of 50 cm. High contrast (0.87) vertical square wave gratings paired with a homogeneous gray field of equal space-averaged luminance were rear projected onto the two screens.

Procedures

The infants and parents were scheduled once every week for 8 weeks. Only one of the two tests was scheduled on each visit such that a vernier estimate was obtained during the intervening week and a grating estimate was obtained every other week in each infant. All the infants started with the vernier test.

The procedures for the vernier acuity test were very similar to the procedures in the previous study (Shimojo *et al.*, 1984). An observer who was blind to the screen looked at the infant's head and eye movements and made a forced-choice judgement as to the side which the infant preferentially fixated. No feedback about the judgement was given to the observer. In the first visit for the vernier test, the infant was tested with 20 min arc of vernier offset for the first 10 trials. If the infant succeeded in reaching the criterion (8 "correct" responses out of 10; $P = 0.055$), he was tested with the next smaller vernier offset (10 min arc). If the infant failed to reach the criterion, then the next larger offset (40 min arc) was tried. Thus, the infants were tested until their performance cut across the level of 75% preference (either from the lower to the upper, or vice versa). Vernier acuity was determined by interpolating the vernier offset corresponding to the 75% level preference on the psychometric function relating percent preference to vernier offset in visual angle. If the infant failed to reach the criterion at any step of the vernier offset, the largest value tested (40 min arc) was used as the estimated vernier acuity. If the infant reached the criterion even with the smallest offset, that value (2.5 min arc) was used as the estimated vernier acuity. In the following (second, third and fourth) visits, the infant was tested with the largest offset yielding 7, or fewer, correct responses out of 10 (subthreshold) in the last visit for the first 10 trials.

For the grating acuity test, exactly the same procedures were employed to obtain comparable data.

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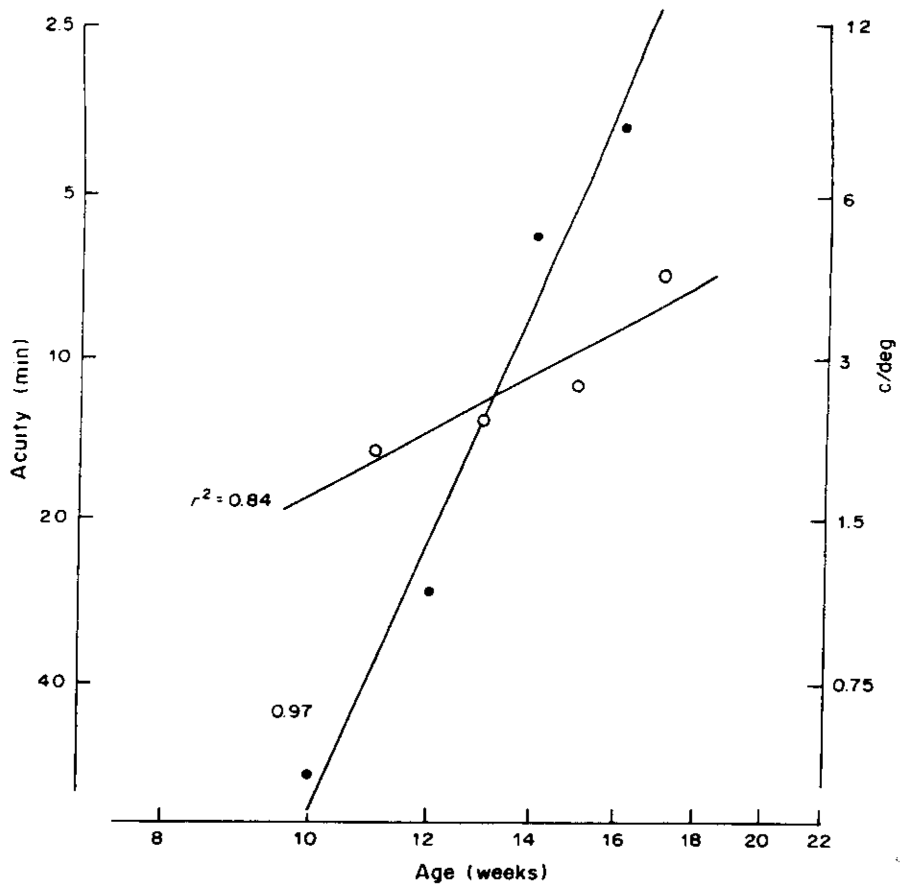

Fig. 4. (A)

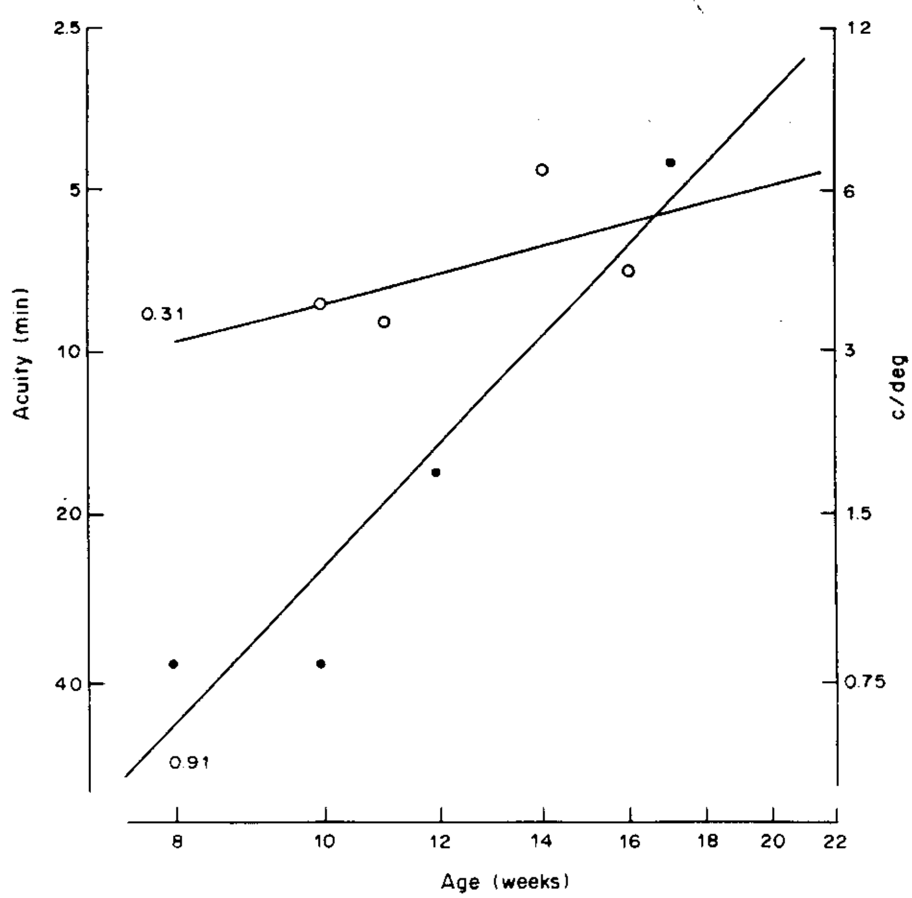

Fig. 4. (B)

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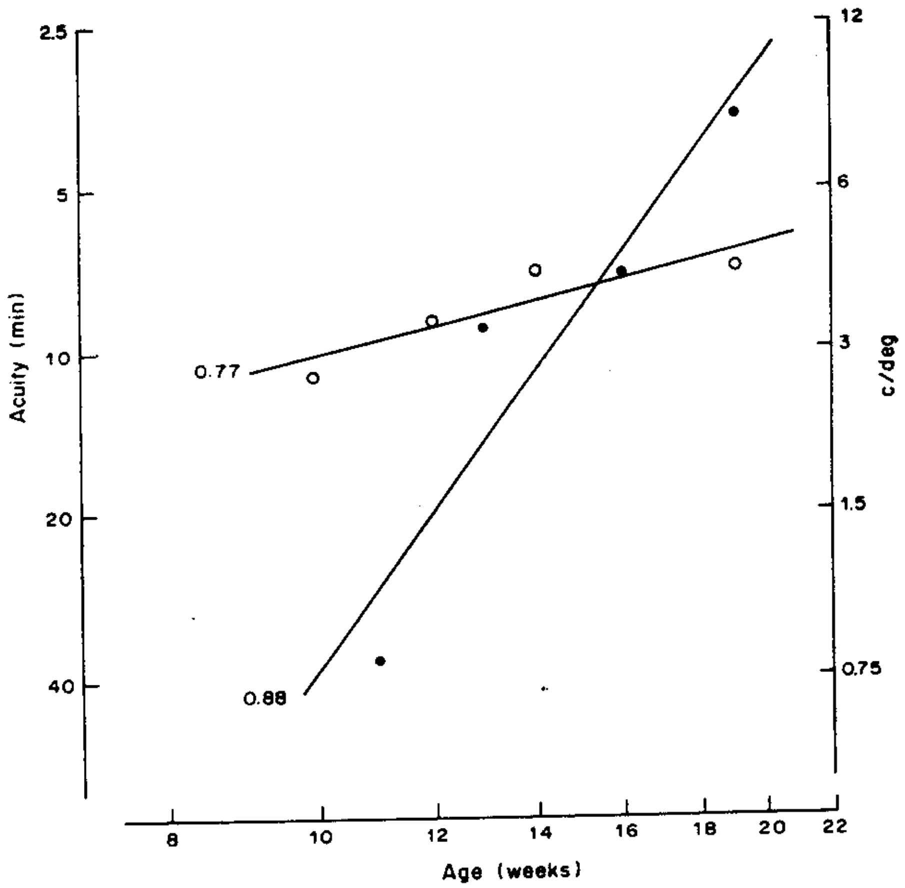

Fig. 4. (C)

Fig. 4. Examples of longitudinal data of vernier and grating acuities. Log acuities (min and c/deg) obtained from four individual infants (A–C) are plotted as a function of age (weeks). Solid circles: vernier acuity. Open circles: grating acuity. Regression lines and r^2 for each acuity are also shown in the figures.

RESULTS

Figure 4(A), (B) and (C) show some typical examples of individual data.* Four vernier estimates (solid circles) and four grating estimates (open circles) of each infant were plotted on each graph of log age vs log acuity. Thirty trials on average were used to determine each estimate. A regression line for 4 estimates of each acuity was calculated and is shown on the graph. *R*-square (r^2) indicating the fit of dots to the line, is also shown for each line. The cross-sectional data with age broken down into two week categories are shown in Fig. 5 in a similar way. Numbers of infants tested for each acuity in each age category are shown at the top of the graph. The results may be summarized in the following two points:

(1) *Vernier acuity was in fact less than grating acuity at young ages*

Comparing the first vernier estimate and the first grating estimate for each infant, 16 out of 22 infants showed less vernier acuity than grating acuity, 4 showed equivalent acuities, and 2 showed higher vernier acuity than grating acuity ($P < 0.001$ from the binomial distribution). The first vernier estimates for the two exceptional infants were higher than their first grating estimates by 0.2–0.7 octave. In the cross-sectional data, mean values of vernier acuity at 9–10 and 11–12 weeks were significantly less than mean values of grating acuity at the same ages ($t = 6.0$, d.f. $= 12$, $P < 0.005$ for the 9–10 weeks; $t = 3.2$, d.f. $= 18$, $P < 0.005$ for the 11–12 weeks).

*It may be more conventional to express grating acuity in wavelength rather than in bar width, in which case the grating data would be pushed downward by a factor of 2.0 in the figures. We chose bar width simply for a better comparison, assuming that it would be more meaningful to express vernier and grating acuity as equal when the amount of vernier offset is equal to the bar width of grating.

7.

(2) The rate (slope of line) of development of vernier acuity is steeper than that of grating acuity

Comparing the slope of vernier acuity and the slope of grating acuity in each infant, 16 out of 18 infants showed a steeper slope in vernier acuity than in grating acuity, and 2 infants showed a steeper slope in grating acuity [the same two as those showing a higher initial estimate of vernier acuity, who were noted in (1)] ($P = 0.002$). Comparison of regression lines (Sokal and Rohlf, 1969) in individual infants indicated that 13 out of the 16 infants, who showed a steeper slope in vernier acuity, showed a significant difference ($P < 0.05$) between the two slopes. One out of the 2 infants, who showed a steeper slope in grating acuity, showed a significant difference ($P < 0.05$) between the two slopes. In the group data (Fig. 5), the slope of vernier acuity was significantly steeper than the slope of grating acuity ($F = 67.9$, d.f. = 1.8, $P < 0.01$).

DISCUSSION

Direct comparisons between vernier acuity and grating acuity measured in the same infants revealed that: (1) vernier acuity is in fact less than grating acuity at the age of 11–12 weeks or younger; (2) the developmental rate of vernier acuity is higher than the developmental rate of grating acuity during the age period of 10–20 weeks.

The results may be attributed to immaturity of motion mechanisms rather than of vernier mechanisms at younger ages since only vernier acuity was measured with a moving stimulus in the current study. But this interpretation is very unlikely because no significant difference has been found between visual acuity measured with static gratings or checkerboards and that with phase-alternated checkerboards at the age of 2 months (Dobson *et al.*, 1978).

There are two other conditions in which vernier acuity is known to be less than grating

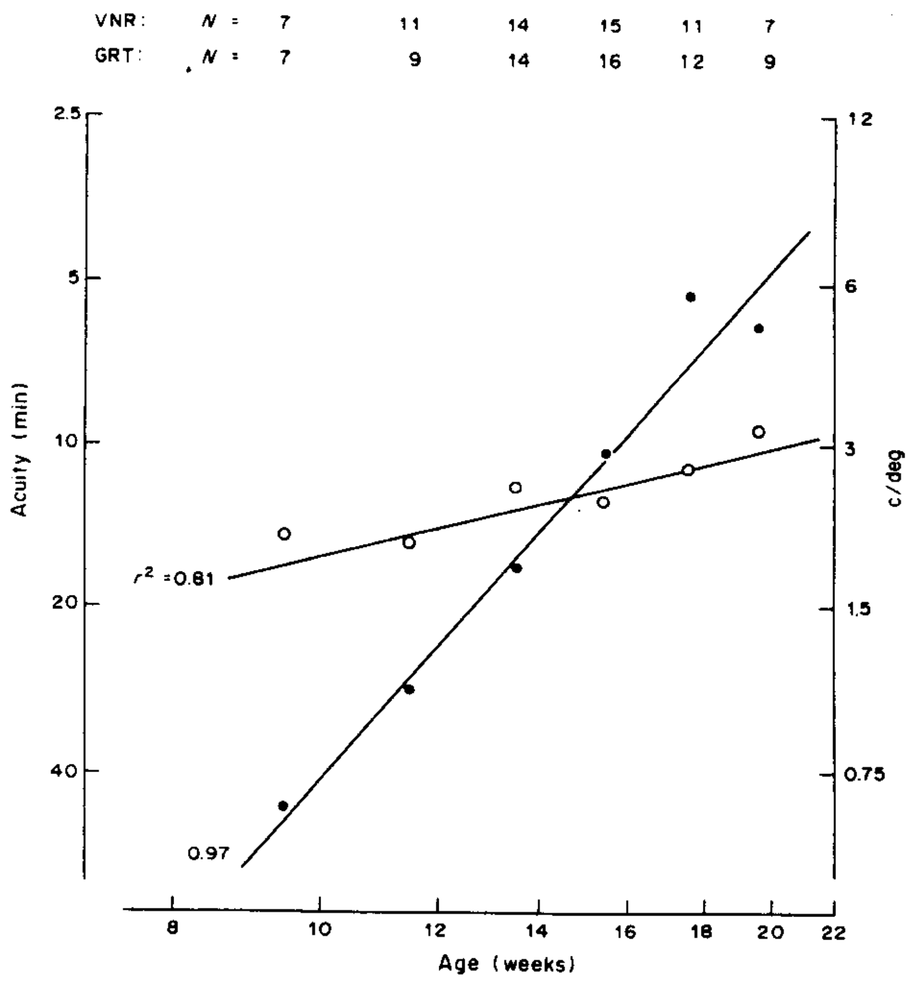

Fig. 5. Group data of vernier and grating acuities. Means of vernier and grating acuities in each two-week age category are calculated, logged, and plotted. Solid circles: vernier acuity. Open circles: grating acuity. Regression lines and r^2 for each acuity are also shown in the figures.

8.

acuity: in the normal periphery and in strabismic amblyopes. For the first case, vernier acuity deteriorates 2–3 times faster than grating acuity as a function of retinal eccentricity (Westheimer, 1982; Levi *et al.*, 1985). For instance, at 10 deg off the fovea, the vernier threshold is 10–14 times higher than at the fovea whereas the grating threshold is only 4–5 times higher (Westheimer, 1982; Levi *et al.*, 1985). Since the grating threshold is 5–8 times higher than the vernier threshold at the fovea, it may be predicted that vernier acuity will be even less than grating acuity at an eccentricity beyond 25–30 deg. Very recently, Fahle and Schmid (in preparation) found that vernier acuity in fact is less than visual resolution when compared at an eccentricity beyond 20 deg. In the second case, Levi and Klein (1982a, b, 1985) found that vernier acuity is degraded more in strabismic amblyopes than in anisometropic amblyopes, relative to grating acuity. They reported vernier acuity which was in fact less than grating acuity in some of the cases of strabismic amblyopia. Levi and Klein (1985) pointed out that unlike anisometropic amblyopia, the primary deficits in strabismic amblyopia cannot be mimicked by blur; that is, they cannot be explained solely by filtering properties. Rather, they are both quantitatively and qualitatively similar to normal peripheral vision in showing a greater loss of position (vernier) acuity than grating acuity. Based on these findings, Levi and Klein (1985) suggested that while the primary deficits in anisometropic amblyopia can be accounted for by the spatial filtering and contrast response properties of visual system, the deficits in strabismic amblyopia are mainly a consequence of spatial undersampling, i.e. a larger mean of center-to-center distance between receptive fields. This notion is basically the same as our speculation about the neonatal visual sampling illustrated in Fig. 3(A). Furthermore, Levi *et al.* (1985) also pointed out that undersampling can result from aberrant position labelling (scrambling) of the mechanisms as well as from a reduction in the number of them. The same is possible in the neonatal retina. For instance, Rusoff and Dubin (1977) speculated that a disappearance of inappropriate, nonselective synaptic connections is required in the horizontal cell-mediated pathways in the retina. Thus, in general, vernier acuity may be less than grating acuity when the distance of spatial sampling is large relative to the size of receptive field. In this case, there may be an analogy among the processes of peripheral vision, strabismic amblyopia and neonatal vision.

Although there is no direct evidence supporting this idea, there is some evidence in the human for post-natal development of the fovea (Mann 1969) and for increasing density of synapses in the striate cortex (Huttenlocher *et al.*, 1982). In kittens younger than several weeks of age (about the same age as the establishment of ocular dominance segregation; Levay *et al.*, 1978), immaturity of receptive fields properties of the retinal ganglion cells (Rusoff and Dubin, 1977), the optic tract fibers (Hamasaki and Flynn, 1977), relay cells in the dorsal lateral geniculate nucleus (dLGN; Glendenning and Norton, 1973; Norman *et al.*, 1975; Daniels *et al.*, 1978), and the visual cortex (Albus and Wolf, 1984) was found. These researchers agree not only that the population of cells showing immature receptive field properties are large, but also that a considerable number of cells are simply unresponsive (e.g. Albus and Wolf, 1984). The number of synapses per neuron in the dLGN also increases in this period (Cragg, 1975). Thus, subcortical visual pathways develop vigorously until a certain age both in animals and humans, which is consistent with the idea of undersampling at early ages resulting in vernier acuity less than grating acuity.

Besides this issue of density and size of receptive fields, development of contrast sensitivity may also affect vernier and grating acuity differentially. There are both qualitative and quantitative changes in contrast sensitivity over the first 6 months of life (e.g. Banks and Salapatek 1978; Pirchio *et al.*, 1978; Atkinson and Braddick, 1981). In particular, the overall level of sensitivity and the peak spatial frequency increase. This change might possibly improve vernier acuity more than grating acuity although in the case of normal periphery, the fact that contrast sensitivity falls off more slowly than does vernier acuity as a function of eccentricity excludes the possibility that it fully explains the degraded vernier acuity (Levi *et al.*, 1985).

Since vernier acuity and grating acuity reflect different aspects of visual sampling and early processing, the comparison between these acuities within individual infants may serve as a significant critical test during the first year of life.

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