Detection of vernier and contrast-modulated stimuli with equal Fourier energy spectra by infants and adults

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Infant and adult vernier acuity differed by a factor of only 4 to 6 when the stimuli were periodic and results were expressed in units of spatial phase. This ratio was much smaller than the factor of 50 to 100 obtained when we expressed our results and those of others in terms of the threshold spatial displacement in visual angle. We compared infant and adult vernier performance to performance on a “benchmark” contrast discrimination task, where the vernier and contrast discrimination stimuli contained identical Fourier contrast spectra. When we compared vernier performance directly to contrast discrimination performance, infant and adult data were remarkably similar, suggesting that similar parts of the visual system limit vernier and contrast performance of subjects of both ages. A control experiment on adults suggested that the superior performance of the contrast discrimination task is due to recruitment of visual pattern analyzers situated at a distance from the discontinuities in phase position and contrast.

Keywords: vernier acuity, contrast sensitivity, contrast discrimination, detection, identification, equivalence class, Fourier phase spectrum

Introduction

Vernier acuity is the misalignment threshold for two nearly collinear lines or gratings. The name is derived from the vernier scale on a calipers or similar device. Detecting such misalignment is common in everyday life, such as when we measure length using a ruler or tell time on a mechanical clock. Vernier acuity is interesting for several reasons. First it is exquisitely fine: A typical normal adult subject can detect misalignments on the order of 10 arcsec of visual angle, which is finer than the spacing of the cones on the retina, even in the fovea. In fact, it is often called a “hyperacuity” for this reason (Westheimer, 1975). Second, vernier acuity is important from a clinical point of view, mostly because it is selectively impaired in strabismic amblyopia, the perceptual disorder that arises from an eye turn during the critical period for visual development. Many strabismic amblyopes, especially those with deficient binocular vision, can readily discriminate between fine black-and-white stripes and a luminance-matched gray stimulus, yet are profoundly impaired on the vernier acuity task (McKee, Levi, & Movshon, 2003). Third, infants, like amblyopes, also show disproportionately lower values for vernier acuity than for grating acuity, compared to normal adults. This is illustrated by the following comparisons from the psychophysical literature:

Three-month-old infants’ vernier acuity is about a factor of 10 worse than that measured on adults. The median infant vernier acuity value across studies is roughly 0.31° of visual angle (v.a.) (Manny & Klein, 1984; Shimojo, Birch, Gwiazda, & Held, 1984; Manny & Klein, 1985; Shimojo & Held, 1987). Typical adult values are 0.003° v.a. or less (Westheimer, 1975; Hess, 1979; Watt & Morgan, 1983; Krauskopf & Farell, 1991).

Three-month-old infants’ grating resolution acuity is only about a factor of 10 worse than that of adults. Typical grating resolution in 3-month-olds is roughly stripewidth = 0.1° to 0.25° v.a., whereas adult grating resolution is about stripewidth = 0.01° to 0.025° v.a. (reviewed in Teller, McDonald, Preston, Sebris, & Dobson, 1986).

The vernier acuity:grating resolution acuity ratio is about 1:1 at 3 months (e.g., Shimojo et al., 1984; Shimojo & Held, 1987) but about 10:1 in adults (e.g., Westheimer, 1975). Before age 3 months, infant vernier acuity is even worse than resolution acuity.

This 10-fold discrepancy between the vernier acuity:grating resolution acuity ratios in infants and adults, together with the selective impairment of vernier acuity in amblyopes, has suggested to some investigators that infant vision and amblyopic vision may be similar. Amblyopia might be a form of arrested visual development (Levi & Klein, 1990b; Kiorpes, 1992; Levi & Carkeet, 1993). If this view is correct, then it is especially important to examine the critical immaturities limiting vernier acuity in infants, as understanding of both normal infant vision and the vision of amblyopes may result.
However, it has proven difficult to articulate a mathematical, testable model of exactly how vernier acuity and grating resolution should be related. The first issue is that they may not share the same sensory neural substrate. If they do not, a single sensory model would have difficulty accounting for both phenomena. Grating resolution acuity taps the responses of channels tuned to the highest visible spatial frequencies, and blur affects grating resolution greatly. On the other hand, blur has little effect on vernier acuity until it is considerable (Levi & Klein, 1990a; Krauskopf & Farell, 1991). This indicates that vernier acuity depends on channels tuned to middle- and/or low-spatial frequencies. The second issue is how to compare vernier acuity and grating resolution quantitatively. Both of them can be expressed straightforwardly in degrees of visual angle: To measure vernier acuity, hold up a ruler marked in degrees, and measure the amount of offset just discriminable from perfect alignment; to measure grating resolution, hold up the same ruler and measure the width of a period of the grating just discriminable from a uniform field. It is also easy to specify grating resolution in cycles per degree at the eye: just mark off a degree and count the cycles. On the other hand, it is not at all clear how to specify vernier acuity directly in cycles per degree. Therefore, a vernier stimulus with a given misalignment (in deg v.a.) is not necessarily “equivalent” to a grating stimulus with a stripe-width (in deg v.a.) of the same numerical value. In view of these difficulties, it is hard to evaluate the significance of the vernier acuity:grating resolution acuity ratio, beyond the in-depth descriptive treatment that the ratio has already received from others.

The purpose of this project was to revisit the question of whether or not infant vernier acuity is, in fact, disproportionately worse than other (more “low-level”) aspects of infant visual performance. The phrase “disproportionately worse” suggests the existence of a benchmark visual function, whose level can be measured empirically and compared directly to vernier acuity because it is expressed in comparable units. By this criterion, grating resolution acuity is not a suitable benchmark for vernier acuity. We note that ideal detector theory has also been proposed as a benchmark (e.g., Banks & Bennett, 1988; but see also Kiorpes, Tang, Hawken, & Movshon, 2003). However, our goal was to avoid the many assumptions involved in relating quantum catch to spatial vision, so we propose a more empirically based approach. This report develops an explicit connection between contrast discrimination and vernier acuity in infant and adult vision (see a similar approach by Hu, Klein, & Carney, 1993). This seemed a promising strategy because sensory neurons in early vision confound stimulus strength with stimulus position relative to the receptive field. Therefore, for any given vernier displacement, there should exist a change in contrast that produces the same size of visual effect on the receptive fields of the individual neurons in early vision. We propose that contrast discrimination could serve as a suitable benchmark by which to judge whether infant vernier acuity is indeed immature.

To this end, we designed vernier detection stimuli and contrast discrimination stimuli with the same Fourier energy spectra, but different phase characteristics. If infants were to perform disproportionately badly on the vernier stimuli, compared to their performance on the contrast discrimination stimuli, the poor vernier performance could not be attributed to low-level immaturities in contrast perception alone. Instead, such a result would suggest critical immaturities in higher level visual processing.

There is already a literature on infant contrast sensitivity and contrast discrimination. Consider the following psychophysical results:

The contrast threshold of 3-to-4-month-old infants at 0.4 cycles/deg is near 0.12, depending on the details of the experiment (the median value of data from Atkinson, Braddick & Moar, 1977; Banks & Salapatek, 1978; Brown, 1994; Peterzell, Werner & Kaplan, 1995). This is a factor of 35 worse than that of adults.

The contrast discrimination threshold of 7-week-old infants is only a factor of 3 worse than that of adults tested in the same experiment using stimuli that are above contrast detection threshold (Brown, 1994; Brown, Lindsey, McSweeney, & Walters, 1995; see also infant data from Stephens & Banks, 1987).

Comparing the numbers from the literature cited above, one might expect that infant vernier acuity, being a factor of 100 worse than that of adults, is disproportionately immature compared to contrast discrimination threshold, which is only a factor of 3 worse than that of adults. If this turned out to be the case for directly comparable vernier and contrast-modulated stimuli, it would suggest that infant vernier acuity is limited by a special, presumably relatively high-level, critical immaturity (Brown 1990) that does not limit contrast discrimination.

It is an attractive hypothesis to suppose that the infant visual periphery is relatively mature, and provides a good visual signal that should allow the young infant to see very well, if only the infant’s brain were mature enough to interpret those signals. However, we have argued (Brown 1990, 1994; Brown et al., 1995) that the insensitivity of the infant visual system to contrast, a relatively low-level immaturity, critically limits infant absolute threshold, increment threshold, contrast threshold, and color vision. There is apparently no need to invoke a special limit for each aspect of infant visual performance; for example, there is no need to postulate that infants lack color-opponent channels (Brown & Teller, 1987) or that they have a special inability to appreciate hue. Consistent with the apparent maturity of high-level sensory function, infant contrast discrimination threshold, although clearly immature (Kiorpes et al., 2003), is remarkably good for stimuli that are above contrast detection threshold. Obviously, if this argument is pushed far enough, infants’ visual performance has to be limited by higher level immaturities, if only because of the limited...
intellectual capabilities of infants. Is vernier acuity the first of these limited, higher level visual functions?

To evaluate infant vernier acuity, we have created corresponding pairs of vernier and contrast-modulated stimuli, which we describe in the next section. Our results show no measurable difference between infants and adults in vernier performance when it is compared to contrast discrimination performance, although the absolute performance of infants (for both types of stimulus) is worse than that of adults. Furthermore, this striking similarity between infant and adult data holds up when the performance of infants and adults on each task is improved by a different amount, by manipulating the spatial configuration of the stimuli. Therefore, these experiments suggest that infant vernier acuity is probably not nearly as immature as previous research has suggested.

**Experiment I**

This project required special stimuli with special properties, so we chose an especially simple vernier stimulus, namely, shifts in the spatial phase of a sinusoidal grating (Figure 1F). A shift in spatial phase of some parts of the stimulus but not others is a nonlinear process, and therefore it introduces harmonics into the Fourier energy spectrum that were not present beforehand; each new harmonic component has a corresponding value in the Fourier phase spectrum. However, many non-vernier stimuli have the same Fourier energy spectrum as the vernier stimulus, but differ from it in the phase spectrum.

All such stimuli may define a single “Fourier-energy equivalence class.” To anticipate a bit, the Fourier-energy equivalence class containing a given vernier offset stimulus also contains stimuli that are modulated only in contrast [constant-phase contrast modulated (CPCM) stimuli]; this study considers the detectability and discriminability of those stimuli.

In this initial description of the stimuli, it will help the reader to consult Figure 1 while reading along in the text. For each panel in the upper half of Figure 1, the corresponding panel in the lower half serves as the legend, and shows symbolically how the test stimuli are put together. The experimental stimuli were based on two components (panels A and B or D and E of Figure 1). These components were never used as stimuli by themselves, but were combined to create the CPCM (panel C) and vernier (panel F) test stimuli. The component stimuli were based on vertically oriented sinusoidal stripes, which were tapered by a Gaussian envelope (a Gabor function) with a maximum of 1.0 and a SD of 1/6 of the half-stimulus display. In one of the component stimuli (panels A and D), the sinusoidal carrier was shifted to the left of cosine phase by 45°, and in the other component (panels B and E), the sinusoidal carrier was shifted to the right by 45°. Thus, the total phase separation between A and B and between D and E was 90°, which places each pair in phase quadrature. The position of the Gaussian envelope was held fixed on both sides of the screen for all stimuli and throughout the experiment.

The components were broken into four segments, numbered a - d (legend in the lower half of Figure 1). Segments a and c were always held at a sinusoidal carrier contrast “a” of 1/√2 (before multiplication by the Gaussian envelope). The carrier contrast “b” of segments b and d was lower, and was manipulated experimentally. Let us consider...
first the stimulus condition in which \( b = 0.19 \). To form a CPCM stimulus (Figure 1C), the component stimuli were added together in such a way that segment \( a \) in panel A was added to segment \( a \) in panel B, segment \( b \) in panel A was added to segment \( b \) in panel B, and so forth. The stimulus \( a, a \) (panel C) had a contrast of 1.0 and a phase angle of zero, which is the vector sum of the \( a \) panels in component A and the \( a \) panel in component B. The stimulus \( b, b \) had a total contrast of \( 0.19 \sqrt{2} = 0.27 \) and a phase angle of zero, which is the vector sum of the \( b \) panels in components A and B. The panel \( c, c \) has the same contrast and phase as \( a, a \), and the panel \( d, d \) has the same contrast and phase as \( b, b \). Figure 1C is the resulting CPCM stimulus.

Now consider what happens when we flip the component in panel B of Figure 1 vertically to form the component shown in panel E, and then combine it with the component in panel D. The contrast of the four segments in the combined stimulus will be equal (panel F: \( a, d; b, c \)), because each is the sum of a component segment with contrast \( a = 1/\sqrt{2} \) and a component segment with a lower contrast (in our example, \( b = 0.19 \)). Segments \( a, d \) and \( c, b \) have a contrast of \( \sqrt{a^2 + b^2} = 0.73 \) and a phase of \( \arctan(a/b) = +15° \) relative to the phase of component \( A \); segments \( b, c \) and \( d, a \) have a contrast of 0.73, but their phase is \( \arctan(b/a) = 75° \). Thus, the resulting combination stimulus is modulated in phase from segment to segment, whereas its contrast is constant throughout. This stimulus can be said to be vernier phase-modulated, with a total misalignment of \( 75° - 15° = 60° \) of spatial phase modulation.

“Catch” stimuli were presented in the opposite side of the stimulus display (left of Figure 2, a and b), as required under the spatial two-alternative forced-choice (2AFC) protocol. They were unmodulated and were in cosine phase relative to the mode of the Gaussian envelope. The same “catch” stimulus was used with both members of a given Fourier-energy equivalence class, and it always had the same contrast as the vernier stimulus. With the exception of the 90° phase offset, the contrast of the catch stimulus was close to the average of the contrasts of segments \( a, b, c, \) and \( d \) of the CPCM stimulus (Figure 1C). When a test stimulus like Figure 1B is flipped rigidly in the vertical direction (around a horizontal axis: compare panels B and E of Figure 1), the spatial phase of the sinusoidal carrier remains the same. Therefore the carriers in panels D and E of Figure 1 are still separated by 90° of spatial phase. Further, the Fourier energy spectrum of Figure 1B does not change in any way. The changes that do occur are restricted to the phase spectrum. Therefore the CPCM (Figure 1C, formed from the unflipped components in A and B) and the vernier phase-modulated stimulus (panel F, formed after flipping the component in panel B to form panel E and adding it to the component in panel E) have equal Fourier energy spectra.

The Fourier energy spectrum, in \( \log_{10} \) units, of both the vernier and CPCM stimuli is shown in two dimensions in Figure 3A. Panels 3B and 3C show the linear energy spectrum as graphs. Figure 3D shows the Fourier phase spectra of a CPCM stimulus (white diamonds) and a vernier phase-modulated stimulus (black triangles). Figure 3 shows that the corresponding vernier and CPCM stimuli, which are made from components with the same contrast values, are Fourier-energy equivalent, and are members of the same Fourier-energy equivalence class.

As an aside, there is evidence that subjects use oriented visual pattern analyzers, with receptive fields of positive or negative slope, to perform vernier acuity tasks (Levi & Waugh, 1995; Ahumada, 1996). The oriented information required for this is clearly visible in the 2D Fourier analysis shown in Figure 3, where all the Fourier energy in the “tracks” is oriented, except that of the fundamental at \( f(y) = 0 \).

**Fourier-energy equivalence**

To see why the notion of Fourier-energy equivalence is a useful one, suppose that the subject detected the vernier offset by just detecting the discontinuity between the misaligned parts of the vernier stimulus. Subjectively, it seems likely that subjects might be able to detect the vernier or CPCM modulation by “looking for the glitch.” Operationally, this is equivalent to simply adding up the magnitudes of the responses of all the neurons (the “analyzers” of Graham, 1989) with receptive fields near the discontinuity. The right- or left-hand stimulus half-field (Figure 2) that contained the stronger harmonic energy is the one more likely to contain the vernier offset or contrast modulation. This strategy would certainly allow a forced-choice vernier misalignment detection threshold to be measured, because vernier stimuli resulting from large misalignments contain more harmonic energy than those that are misaligned by a smaller amount. Such a model says the Fourier energy spectrum determines the detectability of a stimulus, and therefore it would have to predict that all members of a given class of Fourier-energy equivalent stimuli will be equally.

![Figure 2](https://tvst.arvojournals.org/ on 07/01/2018)
detectable. This prediction holds regardless of any nonlinear processing that might take place after the Fourier energy is detected. This may be considered an “energy summation” model, because detection is based upon the total amount of visually effective stimulus energy, added up without consideration of what other stimulus qualities are being signaled by the “analyzers,” and without regard to phase.

**Generality of the argument**

Unequal detection performance for any two members of the Fourier-energy equivalence class containing a vernier offset rules out the use of Fourier contrast energy as a sufficient cue for detection of that vernier offset. It does not matter exactly how the vernier stimulus is broken down into component stimuli, or how the components are reassembled to generate members of the equivalence class. In fact, there are many stimuli in each Fourier-energy equivalence class. Some of the other members of a given equivalence class can be created trivially by flipping the stimuli or their components. Thus, the horizontal mirror-image twin of the vernier stimulus and the vertical mirror-image twin of the CPCM stimuli are also members of the same equivalence class. There are many other members that can be made by proportionate mixtures of these stimuli, and these mixture stimuli are modulated in both contrast and phase. Additional members can be created by modulating or scrambling the phase spectrum separately.

This lack of dependence on the exact way the component stimuli are combined or recombined means that the results of this experiment, and the modeling based on
them, are quite general. This is true in spite of the somewhat arbitrary way in which the contrast-modulated test stimulus was created.

Methods

Technical details of stimuli

The stimuli were generated on a 19" diagonal video monitor using the Neuroscientific VENUS stimulus-generating hardware and software system (Farmingdale, NY). The stimulus field was a gray square, 28 cm on each side, which was subdivided vertically into two parts; each half contained a Gabor stimulus (Figure 2). The Gaussian envelopes defining the Gabor stripes had a SD of 1/6 of the width of the half-stimulus field, and the sinusoidal "carrier" had a spatial frequency of 8 cycles per half-stimulus. Infants viewed the screen freely from a distance of 0.4 m (spatial frequency = 0.4 cycles/deg); adults fixated the center of the screen with the aid of a fixation point, from 6 m (spatial frequency = 6 cycles/deg). This placed the infant stimulus near the spatial frequency of highest contrast sensitivity, and placed the adult stimuli near the spatial frequency that gives the best vernier acuity (reviewed in Wilson, 1986; see also Whitaker & MacVeigh, 1991). Space-averaged luminance was maintained at about 50 cd/m² throughout the experiment, and linearization was maintained using a calibrated look-up table.

The contrast $a$ of the sinusoidal part of component segments $a$ and $c$ (Figure 1) was held at $1/\sqrt{2}$ throughout the experiment, whereas $b$, the contrast of component segments $b$ and $d$, varied between $1/\sqrt{2}$ and zero. The overall phase modulation of the vernier member of the Fourier-energy-equivalent pair was $\text{ArcTan}(1/(b^*\sqrt{2})) - \text{ArcTan}(b^*\sqrt{2})$, and the overall contrast of the vernier stimulus was $\sqrt{(b^2 + 0.5)}$. The maximum contrast of the CPCM stimulus was the limiting factor in determining the contrast of all the stimuli, and was held at 1.0 throughout the experiment. Covariation between the overall contrast and phase offset of the vernier stimuli was tolerated to maximize the contrast of all the members of each Fourier-energy equivalence class.

Units of measure

The relationship between the phase offset of a given vernier stimulus and the contrast modulation of its corresponding CPCM stimulus is at the heart of this experiment. Because the vernier and CPCM stimuli are members of a single equivalence class, the amount of the vernier offset and the contrast modulation depth can be expressed in common units. In this report, the vernier offset in degrees of spatial phase is chosen as the primary unit of measure for both vernier and CPCM stimuli, tagged as "equivalent" vernier offset in the case of the CPCM stimulus. For the convenience of the reader, we report summary statistics in both contrast and equivalent offset units, and we also report infant:adult ratios in units of contrast, phase, and offset at the eye.

Subjects

Fourteen presumptively normal 12-week-old subjects were selected from our infant subject pool. All infants were reported to have been born in good health within two weeks of their estimated due dates, and all were in good health at the time of testing. None of the parents reported any family history of amblyopia or other serious visual disorders. After a parent had provided written informed consent, each subject was tested for up to three daily 1-h sessions, starting within 3 days of his/her 12-week birthday. The average number of trials per daily session was 105 (SD = 56).

All infants were offered a full, dilated, optometric visual exam as a benefit for participation. About half of the infants' parents accepted our offer and were examined after testing was completed. They all had age-normal TAC acuity in each eye, their refractive errors were between −1D and +3D in each eye, with less than 1D anisometropia, and funduscopic and ocular motility evaluations were unremarkable.

The adult subjects were female laboratory personnel aged 20-48 years, and they provided written consent before participating. All adult subjects had received ophthalmic exams within the previous two years, and had been found to have clinically normal vision except for optical correction of myopia (under 2.5D) and astigmatism (under 2D). All wore appropriate refractive correction.

Procedures and experimental design

Infant data were collected using the forced-choice preferential-looking (FPL) method (Teller, 1979), which is analogous to the spatial 2AFC method for adults. Test and catch stimuli were presented simultaneously on the right and left sides of the stimulus display, respectively. An adult observer held the infant in her arms using a "baby sling," standing in such a position that the infant could see the stimulus display, but the adult observer could not. The adult observer watched the infant's looking behavior by means of a closed-circuit video system and judged whether the test stimulus was contained in the right or left-side stripes. The stimulus was initiated by means of a pedal, and remained "on" until the observer indicated the chosen response, using another pedal. All other aspects of the experiment were under computer control, including ordering and presenting the stimuli, tabulating the observer's left-right judgments, and signaling with a tone whether the judgment of test stimulus location was correct or wrong. The stimuli were presented using the method of constant stimuli under a randomized-blocks design.

In the infant experiment, each block of trials contained one example of each of the test stimuli, plus a square-wave "easy" stimulus (4 cycles per half screen). Presentation times were generally 10-20 s, and did not obviously differ be-
tween vernier and CPCM stimuli, as the tester could not determine which stimulus type was presented from the infant's looking behavior. The test stimuli were paired with unmodulated Gabor catch stimuli on the opposite side of the display (Figure 2); the square-wave "easy" stimulus was paired with a uniform gray catch stimulus. The infant looked reliably in the direction of the easy test stimulus, so the adult FPL observer's performance was near 100% correct. For test stimuli with the smallest phase offsets, the observer's performance was near chance (50% correct). Stimulus values were chosen to provide several stimuli in between those extremes. Data sets averaged 31 trials (SD = 8) per stimulus value.

Adult subjects followed a procedure similar to that of infants, except for the following: (1) a fixation point ensured that the stimuli fell on symmetrical parts of the binocular visual field for the 2AFC procedure; (2) subjects made left-right judgments based on their own direct observation of the stimulus; (3) no easy stimulus was used; and (4) stimulus presentation time was 1 s. The computer presented the stimuli and indicated with a tone whether or not the subject's judgment was correct. The adult sessions were run in haphazard order, approximately alternating vernier and CPCM stimulus sessions to complete the data sets. Final pooled data sets had between 100 and 200 trials for each stimulus value.

Each infant or adult subject's score was tallied across sessions, and fraction correct was tabulated as a function of the phase offset of the vernier stimulus or equivalent phase offset of the CPCM stimulus. Average fraction correct performance and SEs were calculated for the group from the individual subjects' detection data.

Results and discussion

Average detection data from infants and adults are shown as psychometric functions in Figure 4, with SE bars evaluated from the subject-to-subject variability. The results with respect to energy summation are clear-cut: neither infants nor adults were able to detect the vernier stimulus as well as the CPCM stimulus. Therefore, an energy summation explanation of vernier offset detection can be ruled out. All subjects must have been doing something other than just detecting the added Fourier components.

If we ignore the overall worse performance of infants and concentrate instead on the relation between vernier and CPCM performance, the infant and adult psychometric functions look remarkably similar. In Figure 5, vernier performance is shown directly as a function of CPCM performance, and the infant and adult data fall near a single elbow-shaped curve. The similarity between infant and adult data in Figure 5 shows that infant vernier detection was neither much worse nor much better than that of adults, when the CPCM data are used as a benchmark. The average maximum fraction correct for infants (for the square-wave “easy” stimuli) was 97% (SD = 3.5%), but the infant data never reached 100% correct detecting the vernier or the CPCM stimuli. The high performance on the easy stimuli suggests that the low performance on the experimental stimuli was not due to overall inattention or to any unwillingness of infants to do the FPL task.

Figure 4. Average fraction correct performance, +/- SEM for detecting vernier and CPCM stimuli by infants and adults. The abscissa is equivalent vernier offset in degrees of spatial phase (below) and in degrees or seconds of visual angle (above). The half-filled squares in the lower left-hand corners represent the constraint that 2AFC fraction correct performance for an offset of 0 deg must be 0.5; the half-filled circle on the infant graph is obtained by linear interpolation for use in Figure 5.

Figure 5. Data from Figure 4 replotted to compare vernier and CPCM performance directly, emphasizing the similarity between infants and adults. The continuous line connecting the adult data is also a reasonable fit to the infant data. The hypothesis that CPCM and vernier detection performance are equal (dashed major diagonal) is incompatible with both sets of data. The half-filled circle is the interpolated vernier performance from Figure 4 as a function of the measured CPCM performance; the square is carried forward from Figure 4. All error bars are ±1 SEM, derived from the variance across subjects.
Thresholds and ANOVAs

Individual thresholds were estimated by linear interpolation to 75% correct. Interpolated vernier threshold (±1 SEM) was 54.4° of spatial phase (±4.5°) for infants, and 14.9° (±0.84°) for adults, a threshold ratio of 3.6:1. The similarity between infant and adult vernier performance was previously hidden in the literature by the confounding differences between infant and adult contrast sensitivity functions. When our results were converted into degrees of visual angle, vernier threshold was 0.378° v.a. for infants, and .007° v.a. for adults, a ratio of 55:1, which is closer to the standard values reviewed above. The infant vernier threshold value, in degrees of visual angle, was comparable to those reported in the literature (reviewed in the Introduction) when the size and contrast of the stimuli are taken into account. The adult vernier threshold value was comparable to those from the literature when the Gabor stimulus waveform is taken into account (Krauskopf & Farell, 1991).

The difference between infant and adult vernier acuity was statistically highly significant by an unpaired t test (t₁₁ = 8.69 (analyzed in deg of phase), and t₁₂ = 11.53 (analyzed in deg v.a.), p < .0001 in each case).

CPCM thresholds can be expressed in two units. In Fourier-energy-equivalent phase-offset units, average infant CPCM threshold was 17.8° ± 1.08° of equivalent phase offset, and adult CPCM threshold was 7.03° ± 1.15° of equivalent phase offset, an infant:adult ratio of 2.53. In terms of contrast, recall that the higher contrast of the CPCM stimulus (panels a, a and c, c in Figure 1C) was always 1.0; the lower contrast (panels b, b and d, d in Figure 1C), was 0.728 for infants, and 0.884 for adults, at the contrast discrimination threshold. The Weber fraction for contrast (AC/C) was 0.373 for infants and 0.131 for adults, a ratio of 2.85:1. This ratio is similar to the factor of 3 we have reported for contrast discrimination (Brown, 1994).

The vernier:CPCM contrast threshold ratio was 3.05 for infants and 2.11 for adults. An analysis in log₁₀ units shows that the difference between them (0.159 l.u. ± 0.661) was not statistically significant.

Analyses of variance were performed on infant and adult data. In each case, the analysis considered three factors: subjects x stimulus type (CPCM vs. vernier) x (equivalent) phase offset. In each analysis, the factor "subjects" was not statistically significant, and did not interact significantly with any of the other factors. The infant analysis revealed that stimulus type was statistically significant (F₁,₁₀ = 9.3035, p < .00005), which is our main result: CPCM modulation was easier to see than vernier phase modulation. (Equivalent) phase offset (F₁,₂₀ = 47.49, p < .00005) was also significant, as stimuli were easier to see if the offsets or equivalent offsets were larger. And, stimulus type interacted significantly with offset, as the psychometric functions converged at higher (equivalent) offset values (stimulus type x phase offset: F₁,₂₀ = 8.197, p = .003). Similarly, the adult analysis revealed that stimulus type was statistically significant (F₁,₃ = 20.714, p = .02). (Equivalent) phase offset

(Fₑ,₆ = 25.64, p = .001) was statistically significant, as was the interaction term (stimulus type x phase offset: Fₑ,₆ = 12.395, p = .007). The vernier:CPCM threshold ratios were 2.8 for infants and 2.1 for adults. After converting them to logarithms and then doing a t test on their difference, t = 0.163, ns.

The statistical significance of stimulus type (CPCM vs. vernier) in both the infant and adult data sets indicates that the separation between the data and the major diagonal in Figure 5 was statistically significant. Infant and adult vernier performance fell statistically significantly short of CPCM performance. This shows that neither infants nor adults performed the vernier task as well as the CPCM task, even though the Fourier energy components were identical in stimuli at equivalent offset values.

Experiment II

We also collected a second data set, using stimuli whose parameters differed slightly from those of Experiment I. Our goal was to make the task easier for infants by increasing the number of discontinuities in the test stimulus, and by increasing the width of the stimulus area at maximum contrast.

Methods

Stimuli

The Fourier-energy-equivalent stimuli in Experiment II were based on the same 8 cycles per half screen sinusoidal grating as was used in Experiment I. The test grating was divided into 16 segments (with 15 discontinuities) (Figure 6), instead of four segments (and three discontinuities) as in Experiment I (Figure 2). The contrast of the envelope of each half-stimulus was uniform in the horizontal dimension, except for being tapered to zero modulation toward the center of the screen. The taper function was 90 deg of a cosine² envelope, and it left an approximately one-cycle-wide gray zone between the right and left halves of the screen. The gray zone was required so the adult observer could discriminate the infants’ preferential-looking

Figure 6. Typical stimuli used in Experiment II. A. CPCM stimulus. B. Vernier stimulus. The circles indicate the sizes of the receptive fields tuned to the carrier frequency in each stimulus (see text for details).
eye movements toward the right or left side of the screen. The actual contrasts and offsets were chosen in such a way that the contrast of the vernier stimulus and the “catch” stimulus was held at 1/√2 throughout the experiment. For a given phase offset \( \phi \), the maximum and minimum contrasts of the Fourier-energy-equivalent CPCM stimulus were \( \cos(\pi/4+\phi/2) \) and \( \sin(\pi/4+\phi/2) \), respectively.

There was every reason to believe that the stimulus used in Experiment II would improve performance, particularly infant performance. The important question was whether this manipulation would lead to data that would refute our conclusions from Experiment I about the relative performance of infants and adults.

### Subjects and procedures

Twelve-week-old infants were tested at a distance of 0.4 m, just as in Experiment I. Each infant was tested with three phase offset values: 13 infants (group A) were tested with 90°, 45°, and 22°, and 11 infants (group B) were tested with 44°, 22°, and 11°. Each infant was also tested with the CPCM stimuli that were Fourier-energy-equivalent to the vernier stimuli. Each block contained each stimulus once, plus a square-wave easy stimulus to verify subject cooperation.

Four adults (females, aged 21–54 years) were tested using the same stimulus design as the infants. Testing was done under the method of constant stimuli. Each stimulus block included vernier stimuli with spatial phase offsets of 11°, 5°, 3.5°, 2°, and 1°, plus the corresponding Fourier-energy-equivalent CPCM stimuli. The adults were tested at 4 m (instead of at 6 m as in Experiment I), so the sine-wave frequency was 4 cycles/deg v.a., which was closer to the maximum of the typical adult contrast sensitivity function. Other procedures for subject recruitment, selection, payment, and optometric examination were as in Experiment I.

### Results and discussion

The results of Experiment II are shown as psychometric functions in Figure 7. Infant and adult contrast discrimination and vernier offset detection performance were both better than in Experiment I, and vernier performance was better relative to CPCM performance. However, performance on the CPCM task was still reliably better than that on the vernier task for both infants and adults.

In spite of the changes in performance on the vernier and CPCM detection tasks, the relative performance on the two tasks by infants and adults remained entirely similar. This is shown in Figure 8, where the infant and adult data fall on a common elbow-shaped curve, albeit a different elbow-shaped curve than that shown in Figure 5. These results show that the basic result of Experiment I remained valid, even when we changed the overall level of infant performance, and even when vernier performance was improved more than CPCM performance. Vernier performance approaches, but does not reach, CPCM performance when the height of the segments of the stimulus is equal to one period of the sinusoidal waveform of the stimulus.

### Thresholds and ANOVAs

Thresholds were obtained from the group psychometric functions by linear interpolation to 82% correct, the lowest level of performance reached by all data sets. Vernier thresholds for infants and adults were 22° and 3.39° of spatial phase, respectively. Thus, the infant:adult vernier phase threshold ratio was 6.48:1. In units of visual angle, average infant vernier acuity was 550 arcsec, and average adult vernier acuity was 8.46 arcsec, a ratio of 65:1. The Weber fractions for contrast (\( \Delta C/C \)) were 0.21 for infants and 0.05 for adults, an infant:adult ratio of 4.22. Equivalent phase offset thresholds were 11° and 2.85° for infants and adults, respectively. The infant vernier:CPCM threshold ratio was 2, and that of adults was 1.2.
The infant data were analyzed using two analyses of variance for groups A and B, respectively. Both analyses showed significant main effects for (equivalent) stimulus offset. Smaller offsets and smaller amounts of contrast modulation produced worse performance than larger offsets (group A: $F_{1,24} = 17.5; p < .00005$ in each case). The difference between the CPCM and vernier stimuli was also statistically significant in each data set (group A: $F_{1,12} = 8.14, p = .015$ and group B: $F_{1,10} = 17.5, p = .002$). However, there was no statistically significant interaction between offset and stimulus type in either group A or group B. There was a statistically marginal difference among infants in overall performance of the harder stimulus set (group B: $F_{10,25} = 7.44, p = .06$), but there was no interaction between infants and either of the other independent variables ($p > .25$ in each case). For the adults, there were statistically significant effects of offset ($F_{3,12} = 91.8, p < .00005$) and stimulus type (the CPCM task was easier: $F_{3,13} = 16.8, p = .026$), as well as an overall tendency for some subjects to do better overall than others ($F_{3,15} = 10.02, p = .032$). There was also a statistically significant interaction between the offset value and stimulus type ($F_{4,12} = 8.76, p = .033$), which is not surprising given that the psychometric functions converge at the highest value. However, there was no statistically significant interaction between subjects and either of the other two main effects.

In short, analyses of variance showed that the difference between performance in detecting the vernier and CPCM stimuli, though small, was statistically significant in both infant and adult data sets. In this respect, the results of Experiments I and II were similar.

**Experiment III**

One important aspect of Experiments I and II was that subjects were asked simply to detect the phase or contrast modulation of the stimuli. This is a general feature of experiments on infants. However, it is of interest to know what happens when subjects are asked to identify the direction of the vernier offset rather than merely detect it, as many amblyopes show little deficit in a vernier detection task (Levi, Klein, & Wang, 1994; Figure 4b). Therefore, we planned Experiment III, in which adult subjects had to identify the direction of the phase or contrast modulation.

Figure 3 showed a Fourier analysis of the stimulus as a whole. Certainly that kind of Fourier analysis is not an appropriate model of the visual system. A more suitable model uses “wavelets” rather than full-field sine-waves, because the receptive fields of visual cells are localized in both space and spatial frequency (reviewed in Graham, 1989). Under such a theory, the harmonic energy introduced by the discontinuities in our vernier and CPCM stimuli is detected and analyzed using only the cells whose receptive fields cover the discontinuities. Only those cells would be expected to show equal responses for detecting equivalent vernier and CPCM stimuli. Other cells, whose receptive fields were restricted to the unmodulated parts of the stimuli, might show different responses to these CPCM and vernier stimuli. Those other cells could be used to mediate CPCM performance by simply comparing the magnitude of the responses in cells preferring the same spatial frequencies and orientations across different locations in the stimulus. They could be used to mediate vernier performance only if their responses encoded a local phase signal, which might then be compared over relatively long distances across the visual field.

In Experiment III, we tried to create vernier and CPCM stimuli for which the energy near the discontinuity predominates (Figure 9). We did this by using stimuli with a single discontinuity located at the point of fixation. The stimuli were tapered in contrast away from the fovea. Thus, the center of the discontinuity had higher contrast than the edges, and the center of the discontinuity was at the position of highest spatial acuity and best attention.

Even this stimulus is not completely without information from the locations remote from the discontinuity, and it is probably not possible to create such a perfect stimulus. In contrast, it is easy to create a stimulus that does not contain the information from the discontinuities, by simply blotting out that part of the stimulus (Figure 9C and 9D). This is the classic “gap effect” manipulation (Westheimer & McKee, 1977; Whitaker & MacVeigh, 1991). If the vernier stimulus is detected mostly using stimulus components present near the discontinuity, then the gap would
make the task nearly impossible; if the CPCM stimulus is
detected mostly using components remote from the discon-
tinuity, then the gap should not have very much effect on
performance, except for the effects due to the slightly more
extrafoveal location, and slightly lower contrast, of the re-
maining, visible parts of the stimulus.

Methods

Stimuli

Stimuli were presented at a viewing distance of 2.6 m,
on a ViewSonic CRT video monitor (Professional series
P815, Walnut, CA) using a Macintosh G4 computer.
Stimuli were viewed centrally, with a single fixation guided by
means of a pair of tiny fixation points affixed to the moni-
tor screen. The Gabor test stimuli were vertically modu-
lated (horizontally oriented) 4.04 cycles/deg green gratings,
gated through a circular 2-D Gaussian envelope with a
maximum contrast of 25% and a SD of 0.8 deg of visual
angle, and viewed within a 4.4-deg square stimulus area
(Figure 9). The test stimuli were presented binocularly, and
had a space-average luminance of 3 cd/m².

Observers

The observers were four visually normal adults, aged
21–55 years. All observers provided written informed con-
sent after the general nature of the experiment was ex-
plained to them. All observers had routine dilated eye ex-
aminations during the previous two years, including refrac-
tion, ophthalmoscopic examination, and visual acuity. All
were visually normal except for refractive correction, which
was worn during data collection.

Procedure

The test stimulus was presented for 100 ms, initiated
by the subject. Between stimuli, the subject viewed the
unmodulated green field (except for the fixation points and
the opaque tape that produced the gap in two of the four
stimulus conditions). Test identification thresholds were
measured using a two-alternative forced identification pro-
cedure, in which the subject judged whether the right or
the left side stimulus was higher in position (vernier stim-
uli) or higher in contrast (CPCM stimuli). After each cor-
rect response, the vernier offset or contrast modulation was
reduced by an amount that was Fourier-energy equivalent
to one degree of spatial phase; after each incorrect re-
sponse, the contrast modulation or phase offset was in-
creased by the equivalent of 4 deg of spatial phase. Thus,
the staircase converged to the 80% correct performance
threshold. For each block of trials, 25 reversals were col-
lected; thresholds were the average of the last 22 reversals
of each staircase. In each block of trials, the gap was either
present or absent, and a single stimulus type was presented
(vernier or CPCM). The order of the blocks was counter-
balanced across subjects.

Results

The thresholds for the four subjects and four testing
conditions appear in Figure 10. When the stimuli were
viewed directly (no gap), vernier and CPCM performance
were similar ($t_{4.4} = -0.515, ns$) and the vernier:CPCM
threshold ratio was 0.937. Near the detection threshold,
subjects reported that both the vernier and CPCM stimuli
looked lumpy and uneven in contrast.

When the gap was present, vernier performance and
CPCM performance were quite different. Vernier perform-
ance particularly suffered, in agreement with results from
many other experiments (Westheimer & McKee, 1977;
Whitaker & MacVeigh, 1991), but CPCM performance
was also somewhat worse ($t_{4.4} = 3.48, p = .04$, after correc-
tion for multiple comparisons). This indicated that when
the two halves of the stimulus abutted, CPCM performance
also depended on the discontinuity.

General discussion

Vernier acuity and contrast discrimination

In all of the experiments reported here, corresponding
vernier and CPCM stimuli had identical Fourier energy
components. Yet, under the conditions of Experiments I
and II, performance levels in detecting the two stimulus
types were different. Why was this so? And, why did this
difference between vernier and CPCM performance disap-
near in Experiment III?
When detecting vernier and CPCM modulation, subjects could have used two different classes of simple pattern analyzers (receptive fields of neurons in early vision; Graham, 1989). Analyzers in the first class (a in Figure 6) covered the discontinuities in phase or contrast. Each of these analyzers, depending on its preferred orientation, phase, and spatial frequency, could respond to the higher order harmonics of the stimuli, and would be well suited to respond to relative phase position or contrast. Analyzers in the second class (b in Figure 6) covered the segments. They did not cover the discontinuities, and therefore they could not respond to the higher order harmonics of the stimuli. They could contribute to these psychophysical tasks only by encoding the absolute phases and contrasts of the segments.

Ideally, the observer could use either source of information (relative phase and contrast from the discontinuities, or absolute phase and contrast from the segments) to do any of the four tasks in these experiments (the vernier or CPCM detection tasks of Experiments I and II, or the vernier or CPCM identification tasks of Experiment III). However, our infant and adult subjects were clearly far from ideal in this sense, because vernier performance was not as good as CPCM performance in Experiments I and II. Perhaps subjects could not use the absolute phase information from the segments (coded in the responses of receptive fields, such as b in Figure 6) to aid in the vernier detection task.

In Experiment I, we suppose that subjects used different receptive fields to do the vernier and CPCM tasks. We suppose that subjects used relative phase and contrast information from the receptive fields that covered the three discontinuities to detect the vernier offsets and CPCM stimuli. However, their detection of the CPCM stimuli was dominated by absolute contrast information from receptive fields that covered the relatively wide segments. Thus, CPCM performance was better than vernier performance.

In Experiment II, we encouraged the use of the relative phase and contrast information by increasing the number of discontinuities. The contribution of receptive fields that covered the discontinuities would have increased (by probability summation if for no other reason). Correspondingly, we reduced the size of the segments to reduce the availability of absolute contrast information. We chose a “wiggle frequency” (Skoczynski & Aslin, 1992) of 8 cycles (16 segments) per screen, because the $2\sigma$ passband of a 1-octave bandwidth 2-D Gabor receptive field that responded optimally to the 16 cycles/screen sinusoidal grating would have covered at least two discontinuities (see Table 2.3 in Graham, 1989; circles in Figure 6). Indeed, vernier performance did approach CPCM performance. However, a small but statistically significant difference between detection of the two stimulus types remained.

In Experiment III, we used foveal fixation, and we tapered the contrast in two dimensions to further optimize the use of the information at the (single) discontinuity in phase. The idea was that receptive fields remote from the discontinuity would be eccentric from the foveal center, and would receive lower contrast stimulation. We did not test infants in Experiment III, because we were interested in strictly foveal, high-attention, high-motivation performance, and because we cannot collect identification data on infants. Under these conditions, we found vernier and CPCM identification performance to be comparable, which validates the use of the CPCM stimulus as a benchmark in studying vernier acuity. Then we introduced a gap between the two segments to investigate performance based only on information obtained from receptive fields remote from the discontinuity. When we did the experiment this way, our results were similar to those of Experiments I and II, in that CPCM identification threshold was lower than vernier identification threshold.

**Infants and adults**

It is remarkable that the relation between vernier and CPCM performance of infants and adults was so similar in these experiments. The differences between the stimuli in Experiments I and II had distinct effects on vernier and CPCM performance, but they did not upset the close resemblance between the infant and the adult data sets (Figure 5 and Figure 8). While the reader may be able to devise a number of ad hoc explanations for this result, the simplest explanation is that the visual perception of spatial stimuli of infants and adults is entirely similar, except for the obvious fact that infants and adults have very different contrast sensitivity functions. Infant and adult subjects both apparently use local information to perceive modulation of phase and contrast, but can additionally use global information to perceive modulation of contrast.

**Contrast modulation as benchmark**

In deciding whether an organism (human adult, infant, patient, animal) has “good” or “poor” vernier acuity, some sort of benchmark is needed. A simple estimate of vernier acuity in units of degrees at the eye does not tell us whether vernier acuity is good or poor because the organism just sees (overall) well or poorly, or whether the organism is particularly talented or impaired in vernier acuity. Traditionally, grating acuity has been used as such a benchmark, supposing that vernier and grating acuities both reflect some general ability of the visual system to perceive fine detail. However, we believe that grating resolution acuity is not a good benchmark, as it is not at all easy to compare vernier and grating acuity quantitatively, and we know of no theory that proposes a strong relation between them. The use of classic ideal observer theory (Banks & Bennett, 1988) as a benchmark is problematic because neither adult nor infant performance is quantum-limited (Kiorpes et al., 2003), and because many assumptions are required to link biophysical principles and psychophysical performance.
We propose the use of CPCM stimuli as a benchmark. Although CPCM stimuli are modulated only in contrast, their Fourier energy spectra can be made to be identical to those of vernier phase offset stimuli. Therefore, performance on the CPCM stimulus can provide an index of how well the organism can see the Fourier energy components of the vernier acuity target. Two organisms can be said to have equally good vernier acuity when the ratios between vernier performance and CPCM performance are equal. By this criterion, infant and adult vernier acuity are equally good (or poor), in spite of the large overall differences between infants and adults in the absolute levels of their performance.

Interestingly, the human vernier acuity is less good than it could be. This is apparently because receptive fields that respond to parts of the stimulus remote from the discontinuities can be compared in their response to contrast, but not in their response to spatial phase. An organism that could compare the phase relations between non-adjacent receptive fields could have better vernier acuity than human beings at any age. Presumably such an organism would have vernier and CPCM performance that are comparable under a wide range of conditions, and also would not show a gap effect. In spite of the fact that human vernier acuity is not as good as it could be, these experiments usefully show that the vernier acuity of human infants and adults is in fact quite similar.

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References


