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Temporal modulation enhances the efficiency of spatial offset discriminations by 6-month-olds

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Abstract

Fourteen- and 24-week-old infants were tested for sensitivity to small position differences under two conditions: (a) the Vernier stimulus was flashed on and off at 1.2 or 4.8 Hz (flash condition); and (b) the Vernier breaks were presented in apparent motion at 1.2 or 4.8 Hz (motion condition). The latter stimulus also contained local flicker cues. Each infant was tested at one temporal frequency with both stimuli. No benefit was shown by 14-week-olds at either temporal frequency from the additional motion and flicker cues. However, 24-week-olds required spatial offsets only one third as large in the motion condition as they required in the flash condition at 4.8 Hz. Ideal observer methodology was used to ensure that the spatial information for both of these discriminations was held strictly equivalent. Increasing sensitivity to flicker and/or motion or uncertainty reduction may underlie the enhancement in discrimination shown by 24-week-olds at 4.8 Hz. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Recent studies have examined the development of position sensitivity, e.g. Vernier acuity ([1–3] [4–6]) and motion sensitivity ([7–12]) during the first postnatal year. These studies present a picture of increasing position sensitivity over this age range, as well as increasing sensitivity to slow movements. Many of the studies that measured position sensitivity did so with stimuli which contained motion or flicker, so it is difficult to determine to what degree these temporal factors may have contributed to estimates of position sensitivity.

The most comprehensive study to date of the influence of temporal modulation on estimates of position sensitivity during infancy is the study by [4]. Skoczenski and Aslin clearly showed in these experiments that some types of temporal modulation enhanced the detection of vernier offsets by 3-month-olds while other types did not. More specifically, traveling offsets were detected better than static offsets, while flashing these offsets in an appearance/disappearance mode at 2 Hz did not enhance detection. Skoczenski and Aslin referred to this latter mode of presentation as flicker; we note also that this stimulus leads to the perception of apparent motion in adults, given the proper spatial and temporal presentation parameters. The Vernier offsets appear to be jumping repetitively on and off the baseline.

Why did this flicker/motion condition fail to enhance detection relative to the static condition for 3-month-olds in the Skoczenski and Aslin study? This stimulus potentially provides the infant with two additional cues for discriminating the unbroken lines on the display from the lines with the Vernier breaks. As Skoczenski and Aslin noted, there is local 2 Hz flicker in the regions with the Vernier offsets and as we noted above, such a stimulus may also stimulate motion-sensitive mechanisms. One explanation for the lack of significant differences between thresholds in the static and flicker conditions is that infants at this age are very insensitive to 2 Hz flicker, or to the slow apparent motion produced by dynamically presenting small spatial offsets. There is evidence that infants are insensitive to low temporal frequency flicker ([13,14]) and that sensitivity to slow movement is also relatively poor ([10,12,8]), so there is some support for this hypothesis in the literature.

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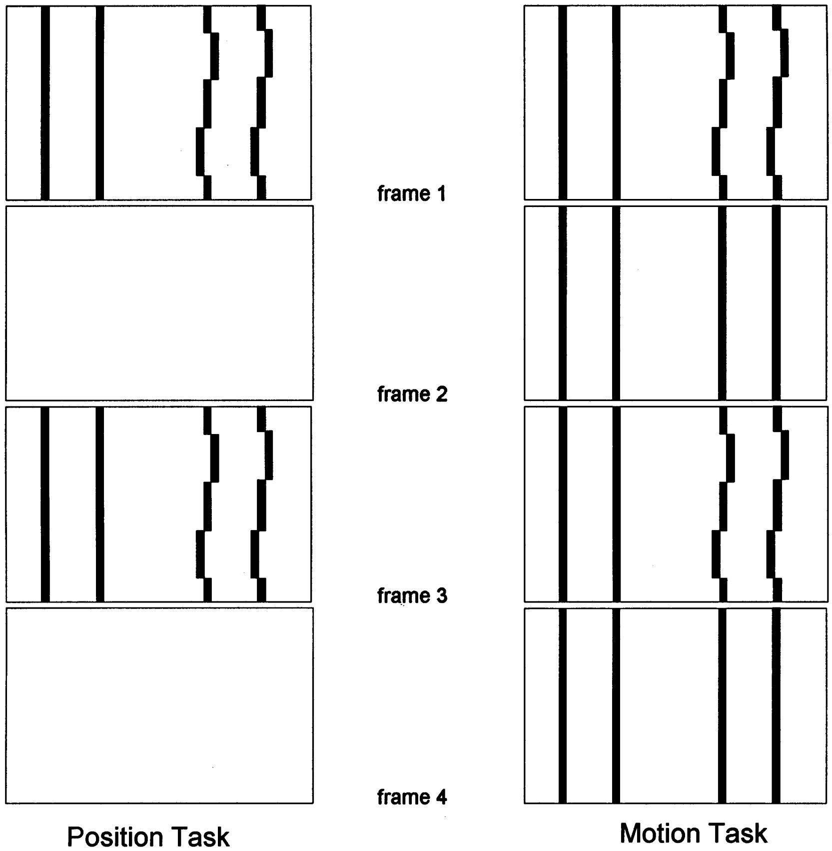

Fig. 1. Four frames from the Flashed (left panel) and Motion (right panel) conditions. The first frames (and all subsequent odd frames) were identical in both conditions. In the Flashed condition, the second frame (and all subsequent even frames) was a uniform field, while in the Motion condition, these even numbered frames were unbroken lines. The alternation of these frames produces apparent motion of the Vernier offsets for the series on the right.

Table 1
Distribution of staircases with zero or one or more bound hits

	Temporal frequency (Hz)				
	1.2		4.8		
Age (weeks)	14	24	14	24	14 (control)
Bound hit status					
One or more bound hits on motion	5	2	0	0	0
One or more bound hits on Flash	6	5	1	4	1
No bound hits on either motion or flash	12	8	11	8	11
n (sample size)	23	15	12	12	12

Comparisons across temporal frequency should be avoided because the staircases started different numbers of steps below the three degree bound at the two temporal frequencies.

In the work reported below, we extended Skoczenski and Aslin's study by: (a) adding an older age group (24 weeks); (b) adding a higher temporal frequency (4.8 Hz); and (c) holding the duration for which the Vernier stimulus was displayed strictly equivalent across the static and moving conditions. We added the older age group and a higher temporal frequency because [15] found improvements in spatiotemporal contrast sensitivity between 4 and 8 months at higher temporal frequencies and [10] found improvements in sensitivity to slow stimulus displacements between 1.5 and 6 months. We redesigned the stimuli because in the [4] study, the Vernier offset was available continuously during a trial in the static condition, but this Vernier offset was available for only 250 ms out of every 500 ms in the flashed condition. The method below ensured

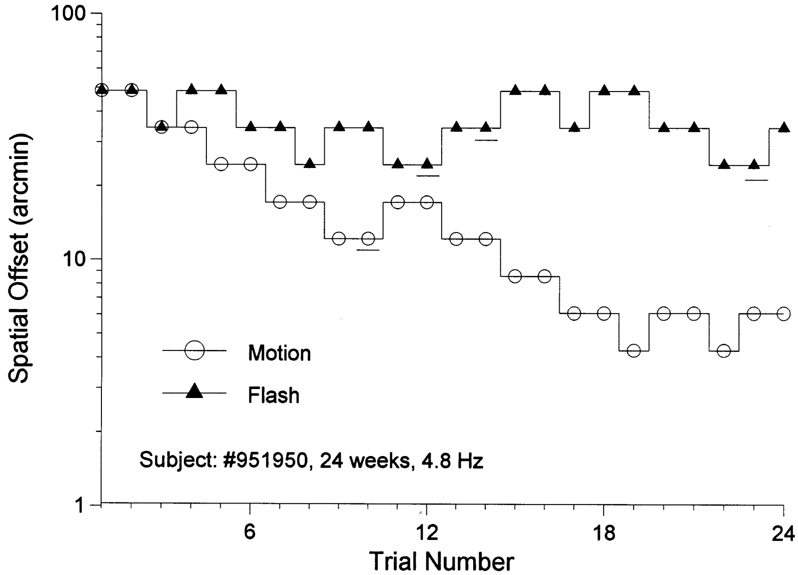

Fig. 2. Example of interleaved staircases for a 24-week-old infant at 4.8 Hz. The trial sequence alternated randomly between the two conditions, so the numbers on the x-axis refer to the ordinal positions of that trial within a staircase. This infant shows an advantage for detecting the Vernier offsets when they are displayed in apparent motion (see Fig. 1, right panel). Threshold was estimated as the average of the last four log offsets presented on each staircase. A trial with a small horizontal bar under it is a miss following a correct judgement at a new amplitude.

that the Vernier information was available for equivalent periods in both of these conditions.

2. Method

2.1. Purpose

The purpose of this experiment was to examine sensitivity within the same infant to a Vernier acuity stimulus and to a stimulus which leads to the perception of apparent motion by adults. We also wanted to hold the spatial information for the two discriminations equivalent. To construct such stimuli, we turned to ideal observer theory and in particular to the analysis of [16] the information for various spatial discriminations at the level of the photon catch in the photoreceptor mosaic. Considerations from this work and the work of [17] led us to devise the pair of stimuli shown in Fig. 1.

On the left side of Fig. 1 are shown four frames from the stimulus that we used to measure position sensitivity. On the right side of Fig. 1 are shown four frames from the stimulus that we used to measure motion sensitivity. Notice that the first (and all odd) frames in both of these stimuli are identical. It is only the second (and all even) frames that differ. In the case of the Vernier stimulus on the left, the second frame is a uniform field. In the case of the motion stimulus on the right, the second frame is a set of straight lines with no Vernier breaks.

The stimuli were designed in this way because they provide an ideal observer with equivalent information over frames. Notice that the second (and all even) frames of both stimuli contain no information relevant to which of the two sides of the display contains the Vernier offsets in the first (and all odd) frames. In other words, these two discriminations are identical spatially from the point of view of an ideal observer (see also [17]).

There is one sense, however, in which the motion configuration may confer an advantage. In the condition on the right in Fig. 1, the unbroken lines are present during each half cycle, while in the configuration on the left, these unbroken lines are absent. One might argue that the presence of the unbroken lines in the motion configuration reduces the observer's uncertainty regarding potential locations for the Vernier breaks. This argument is taken up again in Section 4.

2.2. Subjects

Twenty-three 14-week-olds (M = 98.9 days, S.D. = 5.6, range = 87–116 days) and 15 24-week-olds (M = 171.1 days, S.D. = 5.7, range = 164–181 days) furnished complete data at 1.2 Hz. Twelve 14-week-olds (M = 98.8 days, S.D. = 3.9, range = 92–104 days) and 12 24-week-olds (M = 173.0 days, S.D. = 4.5, range = 166–181 days) furnished complete data at 4.8 Hz. Thirteen 14-week-olds at 1.2 Hz, four 14-week-olds at 4.8 Hz, seven 24-week-olds at 1.2 Hz and zero 24-week-olds at 4.8 Hz were excluded from the final data analysis because they (a) failed to complete all 48 trials, (b) completed all 48 trials but were judged too fussy during the testing, or (c) completed all 48 trials but had bound hits on both staircases (see below).

We also obtained complete data on 12 14-week-olds in a control condition (see below; M = 98.9 days, S.D. = 5.12, range = 91–105 days). Five infants failed to furnish complete or usable data in this control condition; two because of fussiness and three because of prematurity greater than 2 weeks.

2.3. Apparatus and stimuli

The stimuli were presented on a non-interlaced monitor with a 60 Hz frame rate and the line and background luminances were 1.6 and 34.5 cd/m^2, respectively. The contrast of the black lines against the white background was 0.95. The black lines were 20° vertically and 1° wide. The offset portions of the lines were 5° vertically. The middle 5° of each line on the side with the Vernier offsets was never displaced, while the vertically adjacent 5° segments were always displaced in opposite directions. The two lines on each side were separated by 7° and the two lines adjacent to the center of the display were separated by 14° from each other.

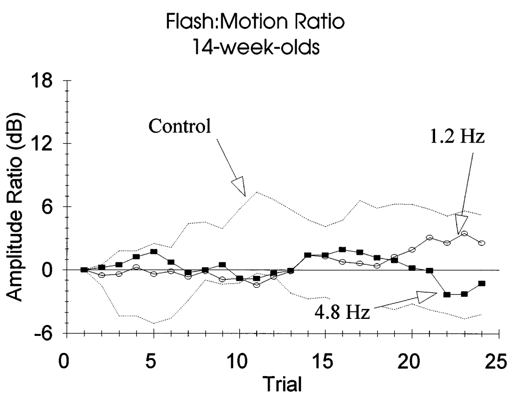

Fig. 3. Group data for 14-week-olds. The average difference in dB between the amplitudes of the staircase for the Flashed Vernier stimulus and for the Motion stimulus (Flashed minus Motion) is shown at 1.2 and 4.8 Hz). One step on the staircase was 3 dB. Positive values indicate greater sensitivity to motion. The dotted lines are the +2 SEM band around the mean difference from the 4.8 Hz Control condition in which two identical staircases were interleaved.

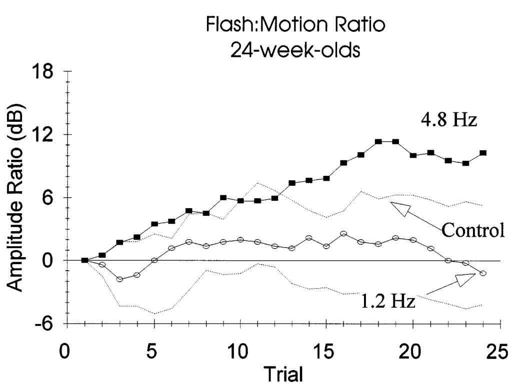

Fig. 4. Group data for 24-week-olds. Same conventions as in Fig. 3. These infants show a significant advantage in detecting these spatial offsets when they are presented in apparent motion at 4.8 Hz.

2.4. Design and procedure

The forced choice preferential looking procedure (FPL; [18]) was used and the FPL observer received feedback about her judgement after every trial. The four stimulus lines (two on each side) gradually appeared on each trial by ramping the luminance contrast of these lines from zero to maximum in 3 s. Amplitude was varied on each staircase using a two-down/one-up procedure with a step size of $\sqrt{2}$ (factor of 1.414). The experiment began with an amplitude believed to be well above the threshold for infants in all age groups.

Each infant was tested using two randomly interleaved staircases—one for the flashed Vernier stimulus and one for the apparent motion stimulus. We ran 24 trials on each staircase. An infant was required to have at least one staircase (flashed Vernier or motion) with no bound hits to be included in the final data analysis. A bound hit occurred when the staircase called for an offset greater than 3°. We accepted data from infants who had one or more bound hits on one staircase but none on the other, because we did not want to bias the results; such a result could indicate a true insensitivity to the stimulus with the bound hits relative to the stimulus with no bound hits. Table 1 shows the distribution of staircases included in the final data analysis, which contained zero, or one or more, bound hits.

The average of the last four amplitudes (not reversals) presented on each staircase was used to estimate threshold in each condition.[1] Both staircases were always started from the same amplitude. Fig. 2 shows an example of staircase data from a 24-week-old subject who clearly showed a large advantage in sensitivity on trials with the apparent motion stimulus.

2.5. Control condition

Twelve 14-week-old infants provided complete data in a control condition in which we interleaved two staircases each using the same 4.8 Hz apparent motion stimulus. We used data from this control condition to estimate measurement error and to examine various

[1] We examined differences on the following measures between the two staircases in the control condition: (a) lowest amplitude reached by the staircase; (b) highest amplitude at which a miss occurred; (c) lowest amplitude at which two consecutive correct judgements occurred; (d) average of all available reversals; and (e) average of the last four amplitudes presented. These measurements were moderately to highly positively intercorrelated. The mean correlation was +0.66 (S.D. = 0.18) and the median correlation was +0.73 (range 0.33–0.82). Additionally, the standard deviations of these measures differed at most by 2.1 dB, so there is little advantage in terms of statistical power of using one of these measures rather than another. The measure that we chose, the average of the last four trials presented on each staircase, is easy to compute, has the advantage of being based on more than one trial (in contrast to several of the other measures) and is based on an equal number of trials from each staircase.

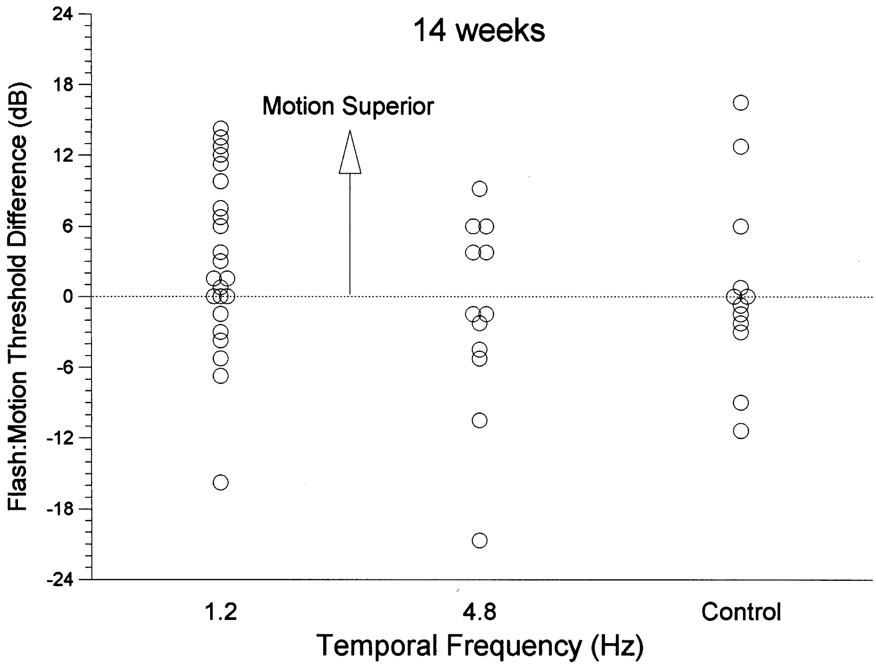

Fig. 5. Individual threshold differences for 14-week-olds at 1.2 (left symbols), 4.8 Hz (middle symbols) and the Control condition (right symbols). Each data point for the 1.2 and 4.8 Hz conditions represents the dB difference in Flashed and Motion thresholds (Flashed minus Motion) for one infant. For the Control condition, each data point represents the dB difference in the last four amplitudes for two interleaved staircases using identical 4.8 Hz Motion stimuli and an arbitrary but consistent direction for getting these differences. A value of 0 indicates that the two staircases were at the same average level after 24 trials on each.

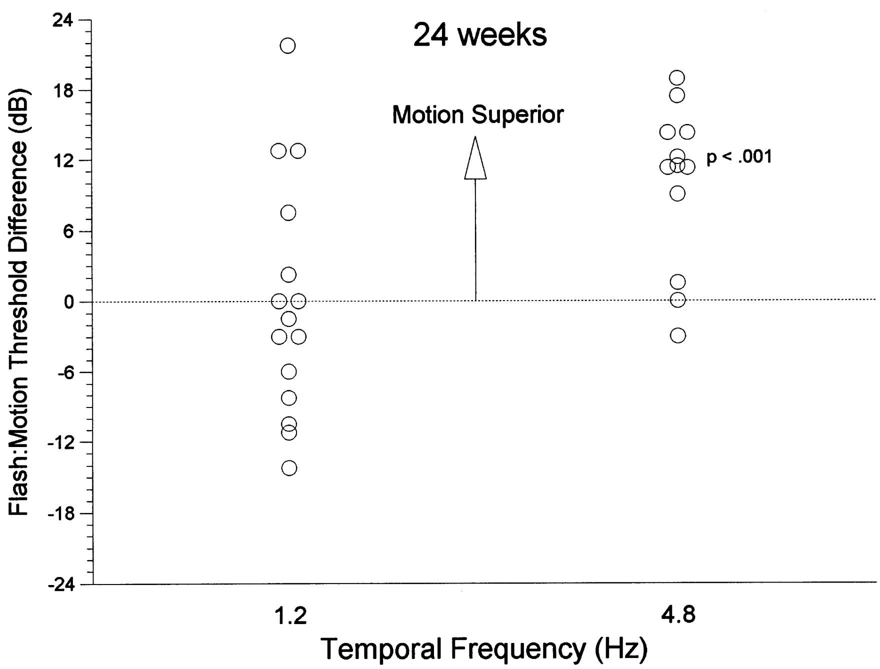

Fig. 6. Individual threshold differences for 24-week-olds at 1.2 (left symbols) and 4.8 Hz (right symbols). Same conventions as in Fig. 5.

ways of estimating threshold with a limited number of trials (24) on each staircase.

3. Results

The first analysis examined group trends on the staircases over trials. For each subject, the amplitude for the flashed Vernier staircase on each trial was divided by the amplitude on the same trial for the apparent motion stimulus and the log of this ratio was multiplied by 20 to convert it into a dB difference. The mean amplitude ratio in dB on each trial is shown in Fig. 3 for 14-week-olds and in Fig. 4 for 24-week-olds. Positive differences indicate that infants were more sensitive to the apparent motion stimulus. One step on

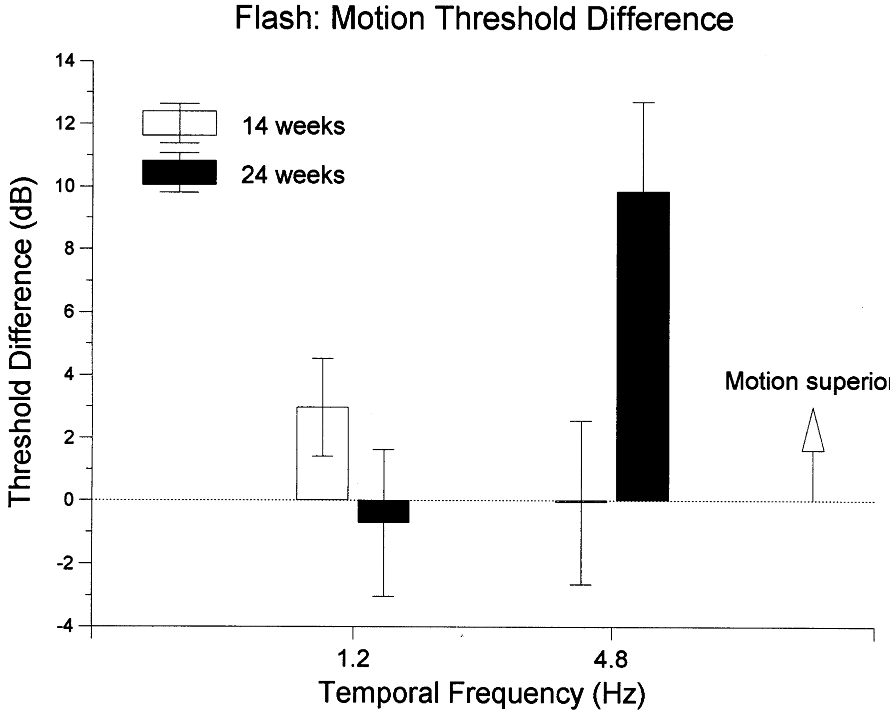

Fig. 7. Mean threshold differences and standard errors at both ages at both temporal frequencies. These are averages of within-subject threshold differences in the Flashed minus the Motion conditions. Only the data at 4.8 Hz at 24 weeks are significantly different from 0.0.

Table 2
Mean average amplitudes and standard errors in minutes of arc for the last four staircase trials in each condition

Temporal frequency (Hz)	Condition	Age (weeks)			
		14		24	
		Motion (M (S.E.M.))	Flash (M (S.E.M.))	Motion (M (S.E.M.))	Flash (M (S.E.M.))
1.2		58.8 (9.02)	82.8 (9.36)	61.6 (12.32)	61.3 (15.14)
4.8		40.4 (11.56)	34.1 (6.45)	19.6 (4.87)	61.5 (15.25)
4.8 (control)	Stair 1	32.7 (9.00)	—	—	—
	Stair 2	35.4 (8.46)	—	—	—

the staircases that we used was equivalent to a 3 dB difference.

The null hypothesis is that infants should be equally sensitive to these two stimuli, so if this were true, then one would expect to see the differences hover around zero across trials in plots like those shown in Figs. 3 and 4. This is mostly true at both temporal frequencies for the 14-week-olds and at 1.2 Hz for the 24-week-olds. There is some indication in the data from the 14-week-olds that the differences may depart from zero near the end of the staircases at both temporal frequencies, but these differences are small—approximately one step on our staircase. The dotted lines in Figs. 3 and 4 from the control condition show that one might reasonably expect mean differences to extend from ± 4 to ± 5 dB over these last four trials from randomly interleaved, identical staircases. Only at 4.8 Hz do the 24-week-olds show a clear advantage in sensitivity to the apparent motion stimulus. By the end of the 24 trials on each staircase for these 24-week-olds, the amplitude for the 4.8 Hz apparent motion stimulus is on average approximately 9 dB lower (a factor of 2.81 or three staircase steps) than the amplitude of the flashed Vernier stimulus.

To test the significance of these differences statistically, the average difference in dB for each infant over the last four trials of the two staircases was computed and used as the dependent variable in a two-way ANOVA with age (14 vs 24 weeks) and temporal frequency (1.2 vs 4.8 Hz) as the independent variables. These threshold differences for all subjects are shown in Figs. 5 and 6 and the means are shown in Fig. 7. The ANOVA showed a significant interaction between age and temporal frequency, $F(1,59) = 10.03$, $P = 0.002$. It is evident from inspection of the individual data in Figs. 5 and 6 and from the plot of the means in Fig. 7 that only at 4.8 Hz for the 24-week-olds was there statistical evidence showing greater sensitivity to apparent motion than to the flashed Vernier stimulus. Out of 12, ten 24-week-old infants tested at 4.8 Hz showed a positive difference favoring motion, one showed no difference and one showed a negative difference. Temporal frequency had a large effect on detection only for the 6-month-olds.

Table 2 shows the thresholds in each condition at the two ages. Thresholds in the flashed and motion conditions were within a factor of 1–1.4 of each other at both ages at both temporal frequencies, with the exception of the 24-week-old thresholds at 4.8 Hz. In this condition, the thresholds differed by a factor of three, favoring the motion condition. The average thresholds ranged from 33 to 83 arcmin in most conditions—values within an octave of those observed by [4] in their study of static Vernier thresholds in 3-month-olds (average 40–45 arcmin).

4. Discussion

Temporal frequency interacted with age and type of stimulus in determining sensitivity to position differences. Only the 24-week-old infants tested at 4.8 Hz benefited from the addition of apparent motion or flicker. Recall that the spatial information for these discriminations was held strictly constant in both the flashed Vernier and apparent motion conditions. Infants at both ages were equally sensitive to these two stimuli at the lower temporal frequency of 1.2 Hz. Flicker or motion at this low temporal frequency does not enhance the detection of small position differences. Flicker or motion at 4.8 Hz however, significantly enhances this discrimination by 24-week-olds. We first compare our results to those of [4]. We then consider several potential explanations for these results.

Two conditions from the [4] study are very similar to the motion and flash conditions in our study. In their Condition 1A, Vernier offsets appeared and disappeared at 2 Hz squarewave in exactly the same manner as did those in the present study. In their Condition 1C, the Vernier offsets were presented with no temporal modulation—in other words, they were static. They reported Vernier thresholds of 36.3 and 41.6 arcmin in these two conditions respectively, for 3-month-olds. Our comparable values were 58.8 and 82.8 arcmin, respectively. Our values were somewhat higher than theirs. Despite the obvious absolute difference in these mean values in the two different studies, we note that our results replicate the finding in Skoczenski and Aslin that there was no significant difference between static Vernier thresholds and Vernier thresholds determined with low temporal frequency apparent motion. At both 2 Hz ([4]) and 1.2 Hz (present study), detection of the Vernier offset is not enhanced by abruptly displacing these offsets creating repetitive apparent motion on and off the baseline.

Why might 24-week-olds show lower thresholds when the offsets are presented in apparent motion at 4.8 Hz than when they are simply flashed at this same temporal frequency in alternation with a uniform field? Perhaps the blank uniform field flashed on each cycle between the Vernier stimuli masked the detection of the spatial offsets. Uniform field masking has been found in adults ([19,20]). It is also possible that integrating the uniform field temporally with the flashed Vernier stimulus could result in lower apparent contrast, making it more difficult to detect the Vernier offsets.

A second explanation for the difference at 4.8 Hz for the older infants is that motion sensitivity is sufficiently mature at this age to provide the infant with an additional cue to the location of the Vernier offsets. In effect, the infant has two types of 'channels' each capable of mediating detection of the target stimulus—spatial channels and motion channels. By 6 months, the motion channels may be more efficient than these other spatial contrast channels in detecting small position differences under the appropriate temporal conditions. We also note that our results are quite consistent with one other study in the literature which used repetitive apparent motion ([21]). Only at 4 Hz and higher did 5-month-old infants show consistent and strong preferences for a large random checkerboard in repetitive apparent motion over a static, adjacent version of the same checkerboard.

Third, it is possible that the better performance which we observed at 24 weeks in the 4.8 Hz condition may reflect detection of temporal contrast (flicker) rather than motion *per se*. Young infants are known to be very insensitive to low temporal frequency contrast changes ([13,14]), so this relative insensitivity may provide the explanation for our negative results at 1.2 Hz at both ages and at 4.8 Hz at the younger age. [15] found clear evidence that temporal frequency had a large effect on detection of spatial contrast over the age range from 4 to 8 months. Specifically, they found primarily an increase in contrast sensitivity at higher temporal frequencies (8 and 17 Hz) from 4 to 8 months. Our results are compatible with those of Swanson and Birch, in that we found that an increase from 1.2 to 4.8 Hz had no effect on the threshold for the 3.5-month-olds, while this same change produced a large increase in sensitivity for the 6-month-olds. An increase between 3.5 and 6 months of age in the ratio of 4.8 to 1.2 Hz contrast sensitivity would produce results like those that we observed.

Finally, as noted above, the presence of the unbroken lines in the motion configuration and their absence in the flashed Vernier configuration may have reduced uncertainty about potential locations for the Vernier stimulus when it appeared during each half display cycle. If this were the explanation for our results, then it would imply that (a) only 24-week-olds benefit from this uncertainty reduction and (b) they only benefit at 4.8 Hz, but not at 1.2 Hz. This latter result is puzzling, because one might expect more certainty when the unbroken lines are displayed longer at the lower temporal frequency.

5. Conclusion

In conclusion, we have shown that when the spatial information is held constant for discriminating lines with Vernier offsets from straight lines, 24-week-olds, but not 14-week-olds, benefit when the spatial offsets are presented jumping on and off the baseline at 4.8 Hz. The superior relative efficiency of this discrimination at 24 weeks may result from increasing sensitivity to motion or to flicker or to uncertainty reduction. In contrast, at 14 weeks these discriminations may be limited by the very coarse spatial sampling at the front end the of the infant's visual system and by poor sensitivity to flicker or slow movement. The addition of the latter cues does little at 14 weeks to enhance the discrimination over levels obtained with purely spatial contrast mechanisms.

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