Temporal Synchrony Deficits in Amblyopia

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Purpose. Amblyopia is a developmental abnormality of visual cortex characterized by spatial processing deficits. Recently, it has been suggested that temporal processing also is affected. We investigated temporal sensitivity by measuring temporal synchrony sensitivity.

Methods. In Experiment 1, we used a contrast detection task to compare the detection of a flickering 3 Hz Gaussian blob to that of synchrony discrimination for a 180° phase shift. In Experiment 2, we measured synchrony thresholds directly by assessing the minimum degree of asynchrony that allowed subjects to discriminate which of 4 high-contrast Gaussian blobs was flickering asynchronously in time (synchrony thresholds). Three temporal frequencies (1, 2, and 3 Hz) and two element separations (1.25° and 5°) were compared.

Results. In Experiment 1, we found that the amblyopes (mean age 19.90 ± 8.59 years, range 11–48 years) exhibited a synchrony deficit only for the 1.25 degrees element separation in the amblyopic eye. In Experiment 2, we also found that the sensitivity for nonstrabismic (pure anismetropia) amblyopes (mean age 15.70 ± 4.00 years, range 12–23 years) was reduced for all three temporal frequencies, whereas for strabismic (strabismus and anisometropia) amblyopes (mean age 24.10 ± 10.03 years, range 11–48 years) it was reduced at 3 Hz only, possibly suggesting a different extent of impairment in temporal synchrony for different types of amblyopia.

Conclusions. Our results suggest that amblyopes have a foveal low-level temporal processing deficit that could explain the previously reported deficit for figure-ground discrimination. (*Invest Ophthalmol Vis Sci.* 2012;53:8325–8332) DOI: 10.1167/iovs.12-10835

Amblyopia traditionally is thought of in terms of a purely spatial deficit as reflected by reduced acuity,[1] reduced contrast sensitivity,[2,3] spatial distortions/inaccuracy,[4–6] and reduced sensitivity for global spatial tasks.[7–10] However, more recently evidence has emerged for a deficit in amblyopia for global motion[11] including optic flow[12] and for the maximum spatial displacement supporting motion perception for random dot kinematograms (Dmax).[13–15] The fact that low level motion performance is thought to be normal in amblyopia[16] raises the question of whether these global motion deficits could be a consequence of the spatial loss in amblyopia.[17] This is unlikely to be the whole story because a recent study showed that the global motion deficit was spatial scale invariant.[18] A recent study provided compelling evidence for deficient time-based figure–ground discrimination in amblyopia using a task where figure was different from ground based on motion onset asynchrony.[19] This could be due to either a low-level temporal deficits or a high-level figure–ground deficit.

Although less attention has been paid to temporal processing in amblyopia, the majority of studies have concerned the temporal dependence of contrast detection,[20–22] and can be explained in terms of a spatiotemporal contrast sensitivity deficit[23] rather than a temporal processing deficit per se. Two studies have provided information on the discrimination of purely temporal events in amblyopes.[24,25] They each used a temporal precedence paradigm where subjects had to discriminate which of two stimuli were presented first. Although both argue for a temporal precedence deficit in amblyopia, the findings disagree as to its dependence of element separation, and eccentricity. St. John did not find any deficit for perceived synchrony (PSE), but did find a sensitivity (JND) difference, but only for stimuli that were sufficiently widely spaced to stimulate different hemispheres.[24] Steinman and Levi did report a perceived synchrony deficit for discrimination rather than detection, but only for closely spaced elements in the fovea.[25] One shortcoming of the former approach is that it compares time differences between central and peripheral areas, rather than within central and within peripheral areas. One shortcoming of the latter approach is that, for the close element spatial separations used, the temporal asynchronies are so short that the contribution of short-range motion mechanisms cannot be ruled out. In fact the investigators conclude that the underlying deficit is motion-based.

In summary, there is evidence for a low-level contrast detection deficit that depends to some extent on temporal frequency,[21,26] possibly a low-level synchrony deficit,[24,25] and a high-level global synchrony-based segmentation deficit.[19] The high-level global synchrony-based segmentation deficit is of particular importance because it occurs for suprathreshold stimuli and involves temporal synchrony rather than contrast detection or image motion. Temporal synchrony of neurons has been advocated as the mechanism underlying binding in object perception.[27,28] Furthermore, it has been shown that neurons driven by the amblyopic eye in strabismic cats, while being normal in other spatial aspects, such as contrast and spatial tuning, exhibit reduced synchronicity of firing.[29] Roelfsema et al.[29] and others[30] postulate that reduced neuronal synchronicity is the basis of the spatial deficits in amblyopia (neural synchrony hypothesis). We hypothesized that the high-level global synchrony-based segmentation deficit[19] has a low-level explanation. We sought to determine whether these hypothesized low-level deficits for synchrony detection in

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amblyopia are limited to the central field and whether they bear a relationship to the spatial disorder as would be predicted by the neural synchrony hypothesis.

EXPERIMENT 1 – DISCRIMINATION OF A FIXED 180° TEMPORAL ASYNCHRONY

Methods

Observers. A total of 20 undergraduate students (mean age 20.30 ± 1.46 years) in National Cheng Kung University participated in Experiment 1. They were naïve to the purpose of the experiment and received additional course credits for their participation. They had normal or corrected-to-normal vision and their dominant eye was determined using the Miles test. A total of 20 amblyopic individuals (mean age 19.90 ± 8.59 years, range 11–48 years, Table 1), of whom 10 were nonstrabismic anisometropes (mean age 15.70 ± 4.00 years, range 12–23 years) and 10 were strabismic amblyopes (mean age 24.10 ± 10.03 years, range 11–48 years) participated in the experiment. They were naïve to the purpose of the experiment. This study followed the tenets of the Declaration of Helsinki, and was approved by the Ethics Committee of the Montreal neurological Institute and the Zhongshan Ophthalmic Center. Informed consent was obtained from all participants before data collection. Strabismic, anisometropic, and mixed amblyopia was defined according to the Preferred Practice Protocol (PPP) from The American Academy of Ophthalmology.

Apparatus. Stimuli were generated using a Macintosh computer (iMac and Mac Pro; Apple Inc., Cupertino, CA) with Psykinematix (KyberVision, Montreal, Quebec, Canada) and displayed on either a 19-inch CRT Monitor (CTX, Taipei, Taiwan) for the results collected at National Cheng Kung University, on a 17-inch CRT monitor (Phillips 107S61; Phillips, Amsterdam, Netherlands) for the results collected at the Sun Yat-sen site, or on a 21-inch CRT Monitor (Viewsonic VX2000; Viewsonic, Walnut, CA) at the McGill University site. The displays had a resolution of 1024 × 768 pixels with a refresh rate of 85 Hz. Observers viewed the screen monocularly at viewing distances of 60 and 240 cm.

Stimuli. The stimuli consisted of four spots each flickering sinusoidally at 3 Hz presented at the top, bottom, left, and right of a presentation screen (Fig. 1). Our choice of 3 Hz was because Forte et al. argue for two systems that underlie the detection of temporal phase differences.[31] The first one operates below 10 Hz and involved the conscious monitoring of phase information across large retinal distances. The second one operates above 10 Hz and involves texture perception. The eccentricity of spots was a 5° visual angle at a viewing distance of 60 cm (peripheral viewing) and 1.25° at a viewing distance of 240 cm (foveal viewing). The spots had a 2-D Gaussian luminance profile in space. The standard deviation (SD) of the Gaussian was 1 degree for the peripheral viewing condition and 0.25 degrees for the foveal viewing conditions. The luminance contrast of spots was modulated sinusoidally in time (contrast reversal flickering). The blobs were presented in a temporal Gaussian envelope to prevent observers from seeing an afterimage. The presentation duration was 1.6 seconds with standard deviations of temporal Gaussian 0.27 seconds. Three of the four spots flickered synchronously, while one, whose position was chosen randomly, had a temporal delay equivalent to a 180° phase shift. The contrast of the blobs was varied to determine the threshold (4 alternative forced choice [4-AFC]) at which this temporal asynchrony could be detected. We termed this the discrimination threshold.

The same configuration was used in the control experiment, but only one spot was presented randomly at one of the four locations. The contrast of the blobs was varied to determine the detection threshold.

Procedure. Discrimination and detection thresholds for a flicker rate of 3 Hz for foveal and peripheral viewing were measured. On each trial, observers judged which spot (4-AFC) was different from the other three spots (discrimination threshold) or at which location the spot was located (detection threshold). A one-up–two-down staircase was used to adjust the contrast of the spots. The starting point of the staircase was high enough to see the spots and to discriminate their synchrony. The size of the downward step of the staircase was set at initially 50% and then moved to 12.5% after the first upward reversal. The upward step size was 25%. The staircase terminated after six upward reversals and the thresholds was calculated as the average of the last five upward reversals. It took approximately 45 minutes to finish the experiment and the order of the conditions was randomized but blocked in terms of viewing distance (i.e., foveal versus peripheral).

Results

The results are shown in Figure 2. The averaged detection and discrimination thresholds are shown in the top row and their scatter plots are shown in the bottom row. Figure 2 shows that performance is significantly different in control and amblyopic groups ($F_{(1,38)} = 20.44$, $P < 0.001$), contrast detection and discrimination threshold ($F_{(1,38)} = 383.49$, $P < 0.01$), and eye of origin ($F_{(1,38)} = 39.85$, $P < 0.001$). The detection thresholds are not significantly different between two groups ($F_{(1,38)} = 1.04$, $P = 0.314$), but the discrimination thresholds are significantly different ($F_{(1,38)} = 28.95$, $P < 0.001$), indicating an impairment in temporal discrimination for the amblyopic groups, involving both for amblyopic and fellow fixing eyes, that cannot be explained simply in terms of visibility. This also can be demonstrated by the scatterplot between detection and discrimination thresholds, where there was no significant correlation between them ($r = 0.02$ and $r = 0.25$ for either peripheral or fovea viewing conditions, respectively). We also found there was no significant difference between the two amblyopic subgroups ($F_{(1,18)} = 0.56$, $P = 0.46$). We also compared the thresholds for subjects above and below 16 years of age to confirm that there is no significant age effect for detection task ($F_{(1,16)} = 1.078$, $P = 0.315$) and discrimination task ($F_{(1,16)} = 0.264$, $P = 0.614$).

Our results demonstrated that there was no significant correlation between the contrast detection and temporal discrimination threshold, and amblyopes have deficits in synchrony processing in both eyes, especially in their amblyopic eye, and the deficit is not related to the visibility of the targets.

EXPERIMENT 2 – TEMPORAL SYNCHRONY THRESHOLDS

Methods

Observers. A total of 22 control individuals with normal or corrected-to-normal vision (mean age 27.6 ± 3.7 years) and 17 amblyopic individuals (mean age 21.6 ± 10.9 years, Table 2), of whom 10 were nonstrabismic anisometropes (mean age 15.6 ± 3.6 years) and 7 were strabismic amblyopes (mean age 31.1 ± 12.5 years), participated in the experiment. The dominant eye of the controls was determined using the Porta point a finger sighting test.[32] This study also followed the tenets of the Declaration of Helsinki, and was approved by the Ethics Committee of the Montreal neurological Institute and the Zhongshan Ophthalmic Center. Informed consent was obtained from all participants before data collection.

Apparatus. Stimuli were generated using a Macintosh computer with Psykinematix (KyberVision) and displayed on either a 21-inch CRT Monitor (Viewsonic VX2000; Viewsonic) or on a 17-inch CRT Monitor (Phillips 107S61; Phillips). The displays had a resolution of 1024 × 768 pixels with a refresh rate of 85 Hz. Observers viewed the screen monocularly at a viewing distance of 60 or 240 cm.

Stimuli. The stimuli configuration was identical to that already described for Experiment 1. The luminance contrast of Gaussian spots also was modulated sinusoidally in time and the contrast of the elements was sampled randomly from normal distribution with mean

TABLE 1. Clinical Data of Patients with Amblyopia for Experiment 1

Subject	Sex	Age	Type	VA AMB Snellen (LogMAR)	VA Good Snellen (LogMAR)	Refraction OD	Refraction OS	Clinical Details	Stereopsis
(1)	M	14	A	0.7 (0.15)	1.0 (0.0)	+7.00/+0.75*0	+3.50/+1.00*75	No previous treatment	400
(2)*	F	12	A	0.05 (1.3)	1.0 (0.0)	+7.50/+0.75*135	+4.50/+0.75*5	No previous treatment	NA
(3)	M	12	A	0.6 (0.22)	1.2 (−0.08)	+1.25/+0.50*75	+0.50	No previous treatment	800
(4)*	F	15	A	0.1 (1.0)	1.0 (0.0)	+5.00/+1.50*115	Plano	No previous treatment	NA
(5)	F	13	A	0.05 (1.3)	1.5 (−0.18)	Plano	+6.50/+0.50*15	No previous treatment	NA
(6)	M	15	A	0.6 (0.22)	1.2 (−0.08)	+0.50*90	+2.75/+1.00*85	No previous treatment	800
(7)	F	13	A	0.6 (0.22)	1.0 (0.0)	−0.75/−0.75*160	+1.00/+0.75*95	No previous treatment	NA
(8)	M	18	A	0.4 (0.4)	1.2 (−0.08)	+0.50	+3.25/+1.25*95	No previous treatment	NA
(9)	F	22	A	0.3 (0.52)	1.0 (0.0)	+6.50	+2.25	No previous treatment	800
(10)	M	23	A	0.2 (0.7)	1.0 (0.0)	+2.25/+1.00*25	−1.00	No previous treatment	NA
(11)	F	23	S	0.1 (1.0)	1.2 (−0.08)	+0.25	Plano	Eso 15 prism diopters, no previous treatment	NA
(12)	M	17	S	0.3 (0.52)	1.2 (−0.08)	+3.50/+1.00*150	+4.50/+1.25*40	Eso 20 prism diopters, no previous treatment	NA
(13)	M	24	S	0.5 (0.3)	1.2 (−0.08)	−3.00	−2.75	Eso 12 prism diopters, surgery and patching	800
(14)	M	19	S	0.2 (0.7)	1.2 (−0.08)	+2.50	+3.50/+1.25*95	Exo 15 prism diopters, no previous treatment	NA
(15)	F	22	S	0.3 (0.52)	1.5 (−0.18)	+1.25	+0.25	Exo 8 prism diopters, surgery and patching	NA
(16)	F	32	S	0.2 (0.7)	1.0 (0.0)	−1.25	−2.00/−0.50*45	Exo 15 prism diopters, no previous treatment	NA
(17)	F	25	S	0.2 (0.7)	1.2 (−0.08)	+0.50	−0.50/−1.00*170	Exo 5 prism diopters, surgery and patching	NA
(18)*	M	11	M	0.3 (0.52)	1.2 (−0.08)	+3.50/−5.25*15	Plano	Exo 25 prism diopters, no previous treatment	NA
(19)	M	48	S	0.32 (0.5)	0.8 (0.1)	−1.50	+2.00 −1.00x75	Eso 3 prism diopters, no previous treatment	NA
(20)	F	20	S	0.4 (0.4)	1.0 (0.0)	Plano	−0.75	Eso 8 prism diopters, patching in childhood	NA

VA, vision acuity; A, anisometropic amblyopia; M, mixed anisometropic and strabismic; NA, not available stereopsis; Exo, exotropia; Eso, esotropia.

* The subject is common between Experiments 1 and 2. The deviation of strabismus was measured by alternate cover test combined with prism correction.

of −10 decibels (dB, 32%) and SD of 2 dB. Three different flicker rates were tested (1, 2, and 3 Hz). The spots were presented in a temporal Gaussian envelope. A presentation duration, which was defined by the SD of temporal Gaussian, was shorter for higher flickering frequency, so that the number of temporal cycles was the same for different temporal frequencies. The SDs of temporal Gaussian were 0.8, 0.4, and 0.27 seconds for flicker frequencies of 1, 2, and 3 Hz, respectively. Presentation duration was defined as 6 SD of the temporal Gaussian.

Procedure. The procedure is the same as for Experiment 1 except the phase offset was varied to determine the synchrony threshold in a 4-AFC task. The difference in temporal phase of one of the 4 flickering spots was varied to determine the minimum temporal synchrony necessary to tell which stimulus was different from the other three (i.e., “4-AFC odd man out” task).

Results

In Experiment 1, we did not find any difference in performance between the two eyes in our control group, thus only the dominant eye’s results were collected for the control group in Experiment 2. Figure 3A shows the results for the control group for peripheral (left column) and foveal viewing (right column). The thresholds in terms of phase angle are plotted against the temporal frequency. A two-way ANOVA with repeated measures (temporal frequency and eccentricity) revealed a significant main effect of eccentricity ($F_{(1,21)} = 8.06$, $P = 0.01$) and temporal frequency ($F_{(2,42)} = 160.34$, $P < 0.01$), but no interactions between them ($F_{(2,42)} = 0.58$, $P = 0.57$). The performance is better for foveal viewing and the thresholds increased with temporal frequency. Thus a linear equation with a zero x intercept (y = ax) was used to fit the data and its slope defines an absolute time delay in milliseconds between peaks of sinusoidal flicker. The fitted results showed that the group average data were described best by a delay of 107.72 ms (38.78°, $R^2 = 0.95$) for peripheral viewing and 99.61 ms (35.86°, $R^2 = 0.81$) for foveal viewing. These results suggested the performance to detect the temporal differences can be expressed as an absolute delay in milliseconds rather than a fixed phase angle in degrees. The shorter the delay time, the more sensitive the visual system is to temporal synchrony.

The results for the amblyopic group are shown in Figure 3B. A three-way ANOVA with repeated measures (eye, temporal frequency, and viewing distance) was performed for 13 subjects who completed all experimental configurations and a significant three-way interaction was found ($F_{(2,24)} = 3.92$, $P = 0.034$). The effects are complicated involving interaction across a number of variables, so they will be discussed first for peripheral viewing and then for foveal viewing. Under peripheral viewing configuration, the main effect in eye of origin ($F_{(1,16)} = 6.068$, $P = 0.025$) and temporal frequency ($F_{(2,32)} = 99.68$, $P < 0.01$) was significant, and there was no interaction between the two factors ($F_{(2,32)} = 1.33$, $P = 0.28$). The group-averaged data were best fitted by a delay of 89.81 ms

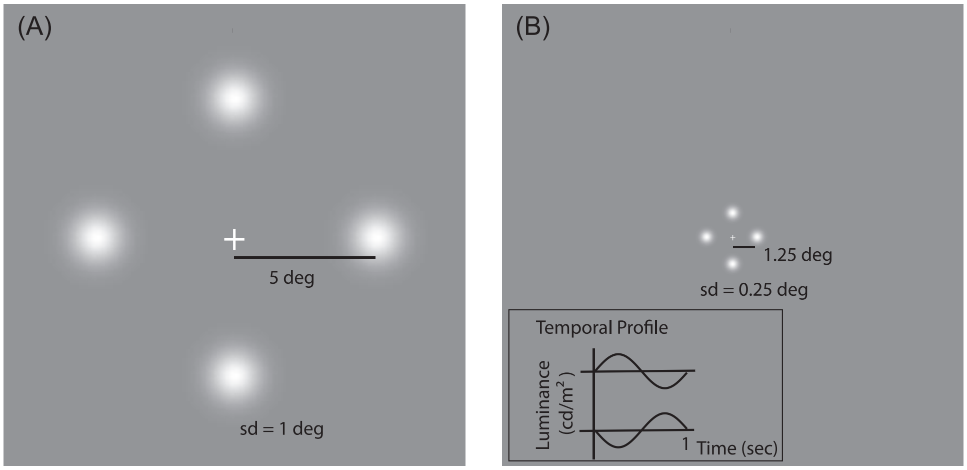

FIGURE 1. Spatial arrangement of the stimuli used in the odd-man-out task. Fixation was always central. (**A**) Peripheral viewing configuration with viewing distance of 60 cm. (**B**) Foveal viewing configuration with viewing distance of 240 cm. *Inset*: temporal profile of the blobs.

($R^2 = 0.93$) for fellow fixing eyes and 102.67 ms ($R^2 = 0.87$) for amblyopic eyes. In summary, the fellow fixing eye was more sensitive to temporal synchrony and the data can be well described by a linear fit, suggesting a pure temporal delay. Under foveal viewing conditions (Fig. 3B, right column), two significant main effects ($F_{(1,12)} = 26.97$, $P < 0.01$ for eye of origin and $F_{(2,24)} = 156.23$, $P < 0.01$ for temporal frequency, respectively) and a significant interaction were found ($F_{(2,24)} = 16.782$, $P < 0.01$). The interaction was due to the higher threshold found in the amblyopic eye at 3 Hz. The group-averaged data were fitted by a delay of 71.31 ms ($R^2 = 0.78$) for fellow fixing eyes and a delay of 113.14 ms ($R^2 = 0.69$) for amblyopic eyes. In summary, similar to the peripheral viewing condition, the fellow fixing eye is more sensitive to the temporal delay than the amblyopic eye.

To compare different types of amblyopia, we plotted the results for the nonstrabismic amblyopes (i.e., anisometropic, Fig. 3C) and the strabismic amblyopes (Fig. 3D) separately. For the nonstrabismic amblyopes, the fellow fixing eye was more sensitive to the temporal delay than the amblyopic eye (86.86 ms, $R^2 = 0.82$ and 101.83 ms, $R^2 = 0.79$, respectively) under peripheral viewing condition. Furthermore, the difference between the amblyopic eye and fellow fixing eye was larger for foveal viewing (68.81 ms, $R^2 = 0.81$ and 116.39 ms, $R^2 = 0.87$, respectively).

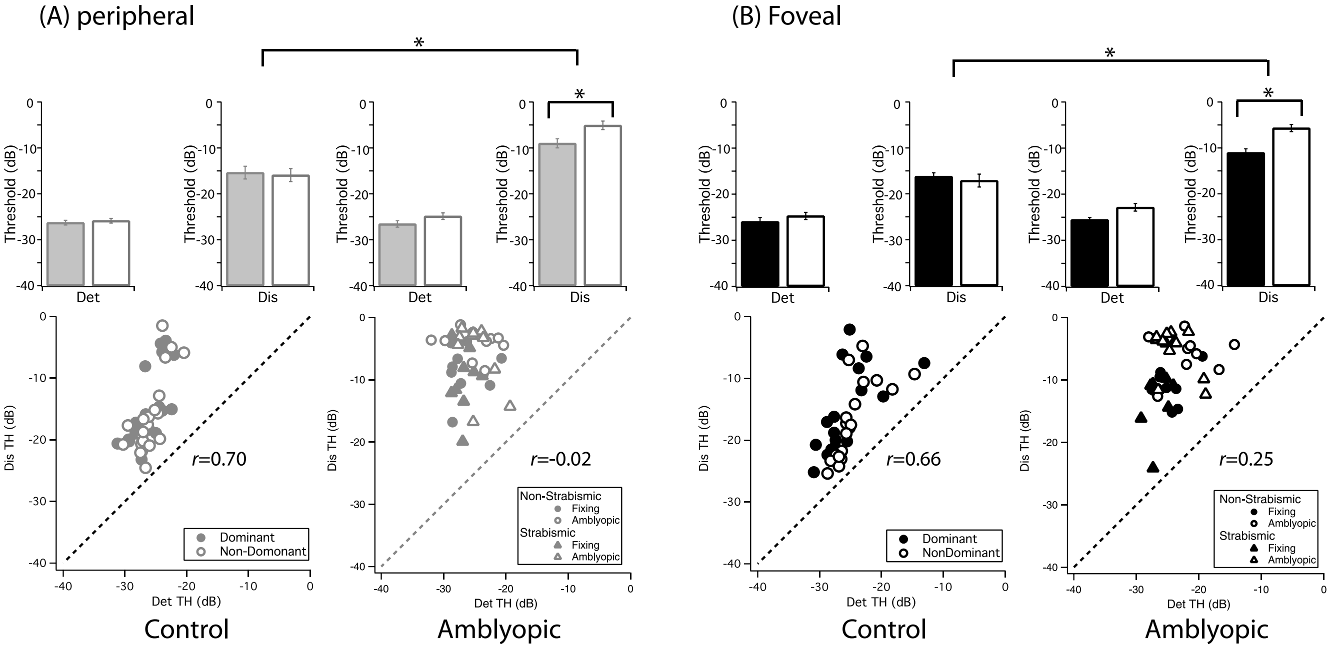

FIGURE 2. Contrast thresholds (*Det*) for the detection of a flickering stimulus and for the discrimination (*Dis*) of its temporal synchrony. Results are compared between the eyes (*open* versus *filled symbols* or *blocks* ± SE) of a normal control group and for an amblyopic group (*open bars* and *symbols* are for the amblyopic eye, and *filled bars* and *symbols* are for the fixing eye) consisting of two sub-groups; strabismic and nonstrabismic amblyopes (*triangle* and *circle symbols*, respectively). Results are shown for peripheral (**A**) and foveal (**B**) viewing conditions in terms of group averages (*top frames*) and detection/discrimination correlations (*bottom frames*). *Brackets* and *asterisks* indicate statistically significant differences ($P < 0.05$).

Table 2. Clinical Data of Patients with Amblyopia for Experiment 2

Subject	Sex	Age	VA AMB Snellen (LogMAR)	VA Good Snellen (LogMAR)	Type	Refraction OD	Refraction OS	Clinical Details	Stereopsis
(1)	Male	18	0.05 (1.3)	1.0 (0.0)	A	−0.50/−1.00*65	+7.00/+0.50*130	No previous treatment	NA
(2)	Female	16	0.2 (0.7)	1.2 (−0.08)	A	−1.75/−0.50*115	+1.00/+1.50*90	No previous treatment	NA
(3)	Male	12	0.5 (0.3)	1.0 (0.0)	A	Plano/+1.75*80	−1.25/+1.50*180	No previous treatment	400
(4)	Male	15	0.3 (0.52)	1.0 (0.0)	A	Plano	+5.00/+1.00*90	No previous treatment	800
(5)	Female	17	0.7 (0.15)	1.2 (−0.08)	A	Plano	+1.25/−4.50*180	No previous treatment	400
(6)*	Female	15	0.1 (1.0)	1.0 (0.0)	A	+5.00/+1.50*115	Plano	No previous treatment	NA
(7)*	Female	12	0.05 (1.3)	1.0 (0.0)	A	+4.50/+0.75*5	+7.50/+0.75*135	No previous treatment	NA
(8)	Male	24	0.1 (1.0)	1.0 (0.0)	A	+5.00/+1.00*90	Plano	No previous treatment	NA
(9)	Male	13	0.3 (0.52)	1.2 (−0.08)	A	Plano	+4.00/+3.00*85	Patching in childhood	800
(10)	Male	14	0.6 (0.22)	1.0 (0.0)	A	+2.00/+1.50*90	Plano	No previous treatment	800
(11)	Female	27	0.125 (1.92)	1.0 (0.0)	S	Plano	−0.5	Eso 6 prism diopters, patching and surgery in childhood	NA
(12)	Female	35	0.5 (0.3)	1.0 (0.0)	S	Plano	−0.25	Eso 10 prism diopters, patching in childhood	NA
(13)*	Male	11	0.3 (0.52)	1.2 (−0.08)	M	+3.50/−5.25*15	Plano	Exo 25 prism diopters, no previous treatment	NA
(14)	Female	41	0.4 (0.4)	1.0 (0.0)	S	Plano	Plano	Eso 8 prism diopters, no previous treatment	NA
(15)	Female	30	0.05 (1.3)	1.0 (0.0)	M	Plano	+4.00	Eso 5 prism diopters, no previous treatment	NA
(16)	Female	20	0.05 (1.3)	1.0 (0.0)	M	+0.5	+2.00	Eso 2 prism diopters, patching in childhood	NA
(17)	Male	48	0.4 (0.4)	0.8 (0.1)	M	−1.50	+2.00 −1.00x75	Eso 3 prism diopters, no previous treatment	NA

* The subject is the one who also joined into Experiment 1. The deviation of strabismus was measured by alternative cover test combined with prism correction.

For the strabismic amblyopes, the fellow fixing eye was more sensitive to the temporal delay than the amblyopic eye (94.00 ms, $R^2 = 0.99$ and 103.89 ms, $R^2 = 0.99$, respectively) under peripheral viewing condition. However, under foveal viewing condition, a paired *t*-test showed there was no difference between the amblyopic eye and the fixing eye at 1 and 2 Hz ($P = 0.10$ and 0.09 for 1 and 2 Hz, respectively), but a large deficit at 3 Hz ($P = 0.01$).

In summary, temporal synchrony thresholds for peripheral viewing were slightly worse for amblyopic eyes, both for nonstrabismic anisometropes and for strabismic amblyopes. However, for foveal viewing, the deficit found in the amblyopic eyes of nonstrabismic ansiometropes occurred across all the temporal frequencies, whereas for strabismic amblyopes the deficit occurred only for temporal frequencies at 3 Hz.

We investigated the relationship between spatial and temporal deficits in amblyopic eyes. The synchrony threshold for amblyopic eyes for 3 Hz stimulation was plotted against their corresponding Snellen visual acuity (Fig. 4). Although we found no correlation between spatial and temporal limitation if all the amblyopic data were collapsed, there was, however, a strong correlation just for strabismic amblyopes for fovea viewing. This may suggest that the 3 Hz synchrony deficit in this group is due to their spatial deficit. However, this may not be the whole story, because their performance at 1 and 2 Hz was relatively normal compared to that of their fellow fixing eye.

Discussion

In Experiment 1, we measured contrast thresholds for detection and discrimination of stimuli of fixed asynchrony (180° phase difference for a 3 Hz flickering stimulus). We found that the eyes of amblyopes were less sensitive than those of the control group, and that amblyopic eyes were less sensitive than fellow fixing eyes for this temporal discrimination, and that this deficit was not due to the reduced visibility of the stimuli. In Experiment 2, we measured synchrony threshold for stimuli of fixed contrast. Amblyopic eyes were less sensitive than fellow fixing eyes and the results could be expressed in terms of a fixed time delay. These data addressed three questions raised in the introduction, namely: Are there temporal discrimination deficits in amblyopia, are these the result of reduced visibility, and do these temporal deficits correlate with the spatial loss?

Are There Temporal Discrimination Deficit in Amblyopia?

Both experimental approaches supported the proposition that there are deficits to temporal processing in amblyopia. When the discrimination was quantified in terms of contrast for a stimulus of fixed asynchrony (Experiment 1), a deficit was measured for both eyes of amblyopes, though slightly worse for the amblyopic eye. This was true for peripheral and foveal stimulation. When synchrony thresholds were used (Experiment 2), a deficit for the amblyopic eye was revealed, particularly at higher temporal frequencies, that was restricted to the fovea.

Are These Deficits the Result of Reduced Visibility?

In Experiment 1, we showed that amblyopes needed more contrast to discriminate the stimulus with the 180° phase lag. Relative to the contrast needed for detection of the 3 Hz stimulus, the amblyopic and fellow fixing eyes needed more contrast than control eyes to discriminate which stimulus was

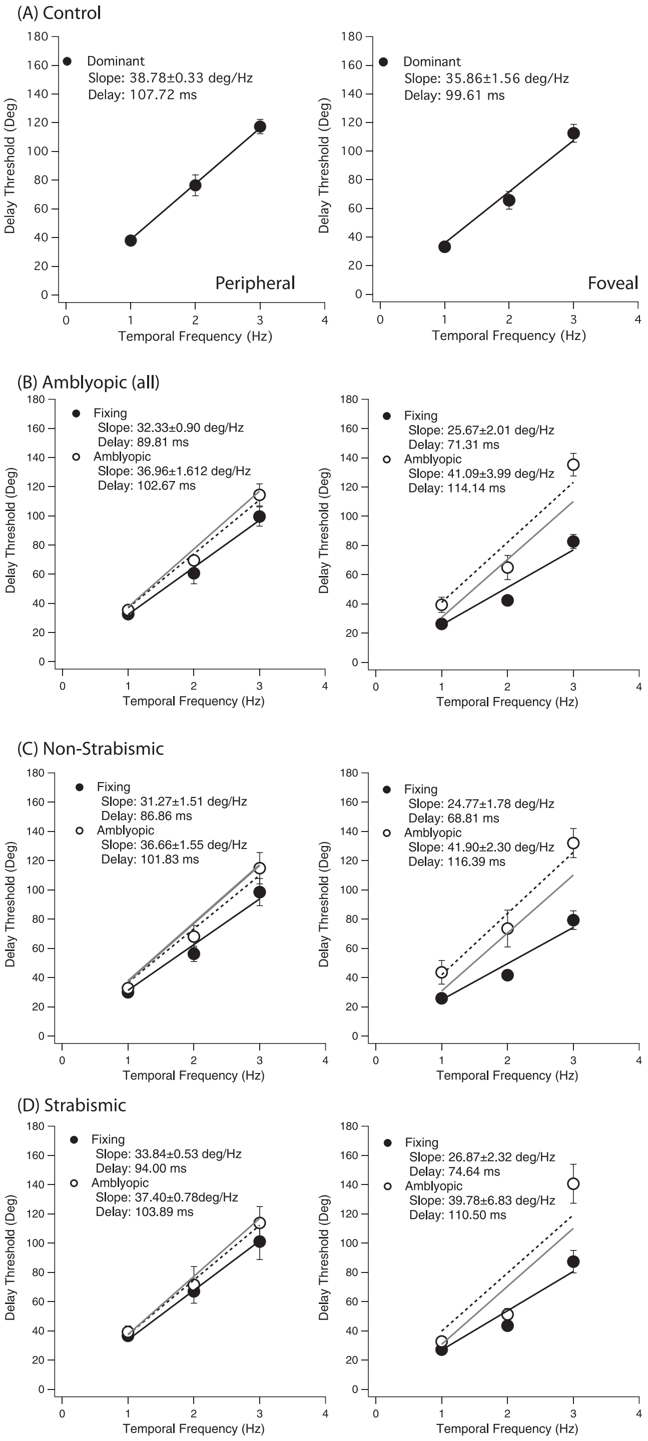

Figure 3. Results are shown for temporal synchrony thresholds for control (**A**) and amblyopic (**B–D**) groups for foveal and peripheral viewing. The threshold is plotted in terms of the phase delay in degrees as a function of the rate of flicker in Hz. *Error bars*: SEs. The slope of the linear fit allows the results to be expressed as a pure time delay in milliseconds and the SD of the slope indicates the goodness-of-fit. The amblyopic group was subdivided into nonstrabismic anisometropic amblyopes (**C**) and stabismic amblyopes (**D**). The fits for control groups are replotted in *light-grey solid line* on the figure of the amblyopic group.

180° out of phase temporally. However, for the amblyopic eye the extra contrast needed to do the temporal discrimination did not correlate with the contrast needed just to detect the stimulus. Thus, the contrast loss and the temporal loss have a different neural basis.

Do These Temporal Deficits Correlate with the Spatial Loss?

One measure of the extent of the spatial loss is the Snellen letter acuity deficit. Although there was no significant correlation between the letter acuity and synchrony threshold loss for the amblyopic group as a whole, there was a significant correlation for the strabismic group for foveal stimulation. Therefore, it is possible that the underlying mechanism could be different in the case of the strabismic versus nonstrabismic amblyopes. In the former case, the spatial and temporal deficits are not independent.

Nature of the Temporal Deficit

It would seem unlikely that the deficits we report could be explained by a single underlying deficit. The deficit revealed by varying contrast while maintaining a fixed asynchrony affected both eyes of amblyopes, central and peripheral stimulation, and strabismic and nonstrabismic amblyopes equally. The deficit revealed by varying temporal synchrony maintaining contrast constant affected only the amblyopic eye, only foveal stimulation, and was correlated strongly only to the spatial deficit for the strabismic subgroup. These differences suggested more than one temporal deficit in amblyopia. The task we used in Experiment 2 is a much simpler one than that used by Spang and Fahle[19] in that it did not require texture segmentation. The deficit we showed involved synchrony threshold of around 100 ms and the deficit also was found in the fellow fixing eye. Furthermore, this deficit cannot be explained by the detectability of the target. In Experiment 2, under peripheral viewing condition, we found amblyopes were more sensitive to temporal asynchrony in their fellow fixing eye (around 90 ms) and had relatively "normal" performance in temporal asynchrony detection (102 ms) compared to the control group (107 ms). Furthermore, under foveal viewing configuration, amblyopes were better in detecting asynchrony (71.31 ms) in their fellow fixing eye, but worse in their amblyopic eye (114 ms). The discrepancy between two experiments might be due to the different contrast levels used; the former was restricted to low contrasts near contrast threshold, whereas the latter involved suprathreshold contrast levels.

RELEVANT SYNCHRONY EXPERIMENTS

Two previous studies argued that amblyopes exhibit a temporal discrimination deficit,[24,25] although they differ on the nature of the deficit. Both studies measured sensitivity for discriminating the temporal precedence of two stimuli. In the study of Steinman and Levi, the deficit that involved discrimination, not detection, was greater the closer the separation between the two stimuli.[25] However, in the study of St. John the deficit, which also involved discrimination (slope of psychometric function) rather than detection (criterion threshold), was present only for well separated stimuli.[24] For both studies, asynchrony thresholds of around 10 ms were measured, an order of magnitude shorter than that for the current task. Since the smallest synchrony threshold for normals for well separated stimuli is around 90 ms,[33] it is likely that these previous approaches contained local contrast or

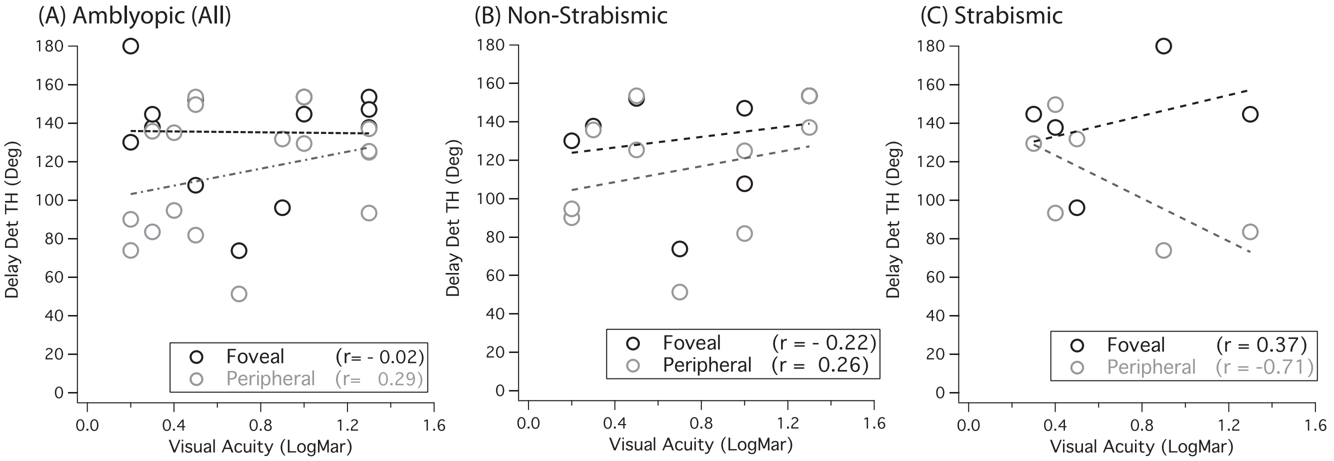

Figure 4. The scatter plot show the relationship between visual acuity (LogMar chart) and temporal (synchrony thresholds) deficits in amblyopic group (**A**). The amblyopic group was subdivided into nonstrabismic anisometropic amblyopes (**B**) and (**C**).

local motion cues, and thus cannot be taken as unequivocal evidence for anomalous synchrony processing. Forte et al. argue for two systems that underlie the detection of temporal phase differences.[31] The first one operates below 10 Hz and involved the conscious monitoring of phase information across large retinal distances. The second system operates at higher temporal frequency and involved comparisons within 0.4° visual angle. Our stimulus configuration matched their so-called "first system," as it was limited to below 10 Hz and involved comparisons over angular distances of greater than 1 degree. Spang and Fahle first reported a pure temporal deficit in a time-based figure–ground segregation task in the amblyopic eye.[19] Their temporal thresholds were not that different from ours (a factor of two lower at most), and their elements were separated by approximately 1.6° and involved a 4.2 Hz frequency, also corresponding to the first system of Forte et al.[31] In this regard, since our task does not involve a texture segmentation aspect, it is tempting to conclude that the original results of Spang and Fahle[19] might be explained by a lower-level more local temporal deficit rather than by one at the site of the more global segmentation operation.

Conclusions

We have followed on from the novel finding reported by Spang and Fahle,[19] who first provided unequivocal evidence for a synchrony-based figure–ground discrimination deficit in amblyopia. We supplied additional information on the following: foveal/peripheral contribution, strabismic/nonstrabismic contribution, and high contrast/low contrast contribution. We support their novel finding and argue for a low-level explanation, one occurring before the computation of figure–ground processing.

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