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Methodological Caveats for Monitoring Binocular Eye Position with Nonius Stimuli

KOICHI SHIMONO,* HIROSHI ONO,†¶ SHINYA SAIDA,‡ ALISTAIR P. MAPP§

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Three experiments, using two sets of Nonius lines placed in a random-dot stereogram, indicated that Nonius alignment does not always reflect binocular eye position and, thus, a caveat is necessary when Nonius alignment is used to monitor binocular eye position. We found that: (a) two Nonius lines with visual line values that differed by up to 7.6 min of arc can appear aligned; (b) the two lines of each of the two Nonius sets continued to appear aligned despite a change in vergence angle of 5.9 min of arc; and (c) the Nonius alignment reflected eye position better, when the binocular dots near the Nonius lines were eliminated. © 1998 Elsevier Science Ltd. All rights reserved.

Binocular vision   Nonius method   Eye position monitor   Visual direction

INTRODUCTION

In many experiments concerned with binocular vision it is crucial to monitor eye position. One common way of doing this is with the use of a Nonius|| alignment stimulus consisting of a pair of non-fusible monocular lines (e.g. Howard & Ohmi, 1992; Nakayama & Shimojo, 1990; Ono, Shimono, & Shibuta, 1992; Shimono, Nakamizo, & Ida, 1994). This method is frequently used because it does not require any elaborate equipment, and the Nonius stimuli can be embedded readily into most binocular stimuli. Although the validity of the Nonius method has been questioned (e.g., Bradshaw & Rogers, 1994; Erkelens & van Ee, 1997a,b; Kertesz & Lee, 1988; Remole, Code, Matyas, McLeod, & White, 1986; Robertson & Schor, 1986), it continues to be used. This paper examines the validity and reliability of the method, when the Nonius lines are embedded in a random-dot stereogram.

The way in which the alignment (or non-alignment) of the lines in the Nonius stimulus inform the experimenter about the position of the observer's eyes is illustrated in Fig. 1, and is best understood in light of the Wells–Hering's laws of visual direction. These laws of visual direction have been discussed in detail elsewhere (see e.g., Ono, 1979, 1991; Ono & Mapp, 1995; Grind, Erkelens, & Laan, 1995). Those stated in Ono & Mapp (1995) are listed below.**

> Law 1. The nodal point of each eye transfers to that of the cyclopean eye, and all visual lines that transfer to the cyclopean eye become visual directions (or cyclopean visual lines).
>
> Law 2. The visual axes transfer to the common axis (or cyclopean visual axis).
>
> Law 3. The angle between any visual line and the visual axis of an eye transfers unaltered to the cyclopean eye.

If the two monocular lines of the Nonius stimulus appear in the same visual direction (as depicted in Fig. 1, panel B1) or have the same visual line value, it is inferred from the laws of visual direction that the eyes are converged on the stimulus plane. This is so, because for this percept to occur, each of the monocular lines must fall on its respective visual axis, or on two visual lines with the same value (see Fig. 1, panel C1). If the two monocular lines of the Nonius stimulus appear in two different visual directions, then dependent on their relative positions it is inferred from the laws of visual direction that the eyes are either converged in front of the stimulus plane (see Fig. 1, panel B2) or beyond the stimulus plane (see Fig. 1, panel B3). This is so, because for these percepts to occur the visual lines of each eye must differ by some angle from their respective visual axes, and as specified by the laws of visual direction this angle is transferred to the cyclopean eye (see Fig. 1, panels C2 and C3).

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*Communications Research Centre, Ottawa, Canada.
†ATR Human Information, Processing Laboratories, Kyoto, Japan.
‡National Institute of Bioscience and Human Technology, Ibaraki, Japan.
§Department of Psychology, York University, 4700 Keele St, North York, Ontario, Canada M3J IP3.
¶To whom all correspondence should be addressed: Department of Psychology, York University, 4700 Keele St, North York, Ontario, Canada M3J 1P3 [*Email*: hono@yorku.ca.].

||The name "Nonius" is from "the Latinized name of Pedro Nunez, a sixteenth century Portuguese mathematician who invented an early form of the vernier scale" (Howard & Rogers, 1995, p. 55).

**For a definition of the terms used in the laws see Ono & Mapp (1995, p. 238).

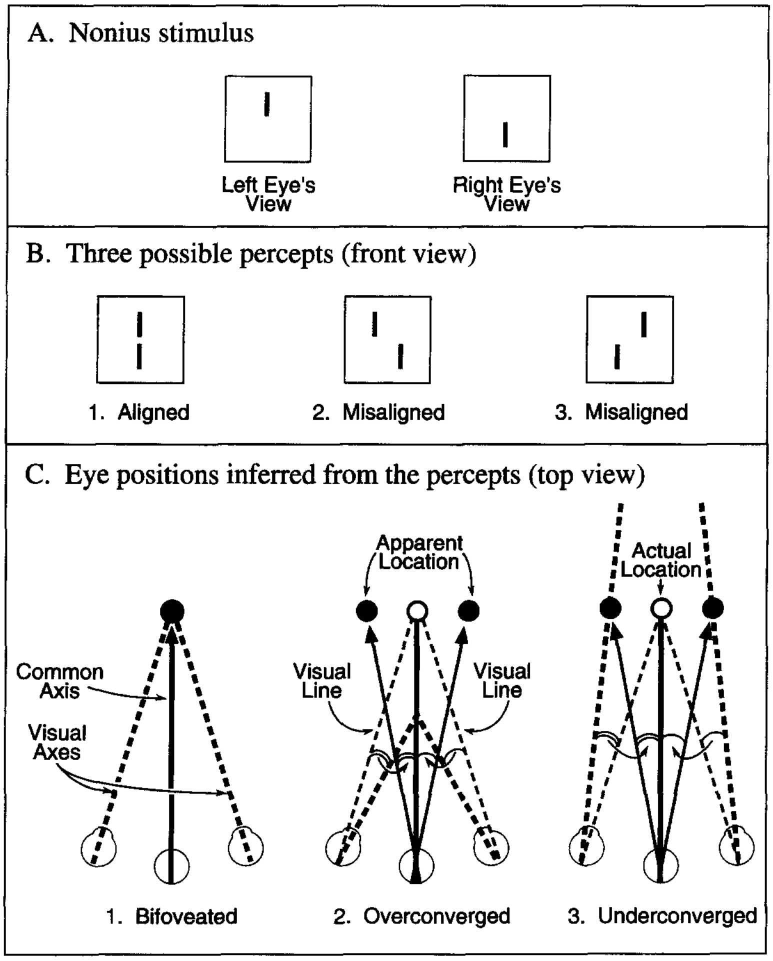

FIGURE 1. An illustration of a Nonius stimulus (A) and how the three possible percepts shown, in (B), indicate the binocular eye positions, shown in (C).

An implicit assumption underlying the Nonius method is that the angle between all visual lines and the visual axis of an eye transfer unaltered to the cyclopean eye. This assumption has been challenged recently, however, in a number of studies in which the stimulus consisted of a random-dot stereogram. For example, Ono (1991) and Ono & Mapp (1995) reported the results from experiments in which they found that the visual directions of Nonius lines differed from their respective visual line values*. Also, Ono, Shimono, & Saida (1997) reported several instances of what they called "a transformation of the visual line", in which the visual direction values of stimuli differed from those of their visual lines. Moreover, Erkelens & van Ee (1997a,b) reported an instance of what they called "capture of visual direction", in which the visual line value of a monocular object positioned adjacent to binocular objects did not transfer faithfully to the cyclopean eye. These findings clearly question the validity and reliability of the Nonius method.

The purpose of the present study, therefore, is to determine the extent to which the visual line values of Nonius stimuli are transformed when Nonius lines are embedded in random-dot stereograms. Determination of the extent of transformation in different conditions will serve to suggest when the Nonius method can and cannot be used to monitor binocular eye position. In three separate experiments, observers were presented with random-dot stereograms in which were embedded two sets of Nonius lines. One set was embedded in the outer area of the stereogram (typically referred to as the stimulus plane), and the other in the inner area (typically referred to as the depth plane). In Experiment 1, observers maintained alignment of the Nonius lines in the outer area, while adjusting the position of the lines in the inner area so as to appear aligned also. In Experiment 2, binocular eye position was monitored objectively while observers switched fixation between the outer and inner areas of the stereogram, which appeared at different depths, while the Nonius lines appeared aligned. In Experiment 3, the proximity of the Nonius lines to the binocular dots in the inner area was manipulated, and once again observers adjusted the position of the lines in the inner area so as to appear aligned, while maintaining alignment of the Nonius lines in the outer area.

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*The results described in Ono (1991) provided the groundwork for Experiment 1 in the present study, and were presented at The Optical Society of America meeting (1986). The results described in Ono & Mapp (1995) provided the groundwork for Experiment 2 in the present study, and were presented at the International Conference and NATO Workshop on Binocular Stereopsis and Optic Flow (1993).

EXPERIMENT 1

Experiment 1 was designed to measure the accuracy and precision of the Nonius method when it is used with random-dot stereograms. In this experiment, observers adjusted the horizontal position of a set of Nonius lines until they appeared aligned, while maintaining fixation on a second set of fixed Nonius lines which continued to appear aligned throughout the trial. If the Nonius method reflects binocular eye position accurately (i.e., all visual line values are transferred unaltered to the cyclopean eye), then the two sets of Nonius lines (the adjustable set and the fixed set) will appear aligned only when they have the same horizontal visual line values. If, on the other hand, the Nonius method reflects binocular eye position inaccurately (i.e., the visual line values are transformed), then the two sets of Nonius lines (the adjustable set and the fixed set) will appear aligned despite having different horizontal visual line values. Moreover, the magnitude of the difference in the visual line values of the two adjustable Nonius lines when both sets appear aligned, will serve as a measure of the accuracy of the Nonius method, and the probable errors computed from the adjustments will indicate the precision of the method.

Method

Observers. Eight members of the university community, four females and four males ranging in age from 22 to 37 years, participated. All reported having normal or corrected to normal visual acuity and stereopsis.

Stimuli and apparatus. The stimuli were generated by a Grinell Graphic System which was controlled by an LSI 11/23 computer. They were displayed on a Hitachi HM-2713 monitor which was positioned such that its centre was at eye level, at a distance of 100 cm from the observer's corneal plane. With the use of polarized filters the left half of the screen was visible to the right eye only and the right half of the screen was visible to the left eye only. The convergence distance was approximately 34 cm, and a −2.0 dp lens was placed in front of each eye to match the required accommodation to the convergence distance.

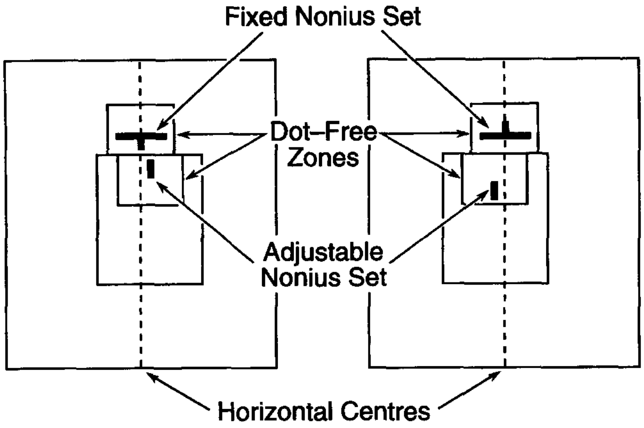

FIGURE 2. A schematic representation of the random-dot stereogram used in Experiment 1. The two sets of Nonius stimuli were presented in the dot-free zones of the random-dot stereogram. The upper set was fixed at the horizontal centre of the outer area of the stereogram, and the horizontal position of the lower set was adjustable. Note that the lines enclosing the various areas of the stereogram were not present in the experimental stimulus, and that the vertical dimension of the stereogram is reduced to save space.

The stimulus, which is depicted schematically in Fig. 2, consisted of a random-dot stereogram in which two sets of Nonius stimuli were embedded. The stereogram was composed of a pair of rectangular areas, (one presented to each eye), of 112 × 256 picture elements each. The inner area of each half of the stereogram consisted of a rectangular area of 56 × 53 picture elements. Each of the picture elements subtended 3.2 × 2.9 min of arc. With respect to the outer area, the inner area was presented with either no disparity or with crossed or uncrossed disparities of 6.5, 13.0, 19.4 or 25.9 min of arc. One of the two sets of Nonius stimuli, the fixed set, was embedded in the outer area of the stereogram and the other, the adjustable set, was embedded in the inner area. The fixed set consisted of a pair of horizontal red lines (48.8 × 7.2 min of arc) and a pair of vertical red lines (6.5 × 11.2 min of arc). The vertical lines were fixed at the horizontal centres of the outer areas. The adjustable set consisted of a pair of vertical red lines (4.9 × 14.4 min of arc) separated vertically by 4.2 min of arc. Both sets of Nonius stimuli were presented in a white rectangular space (65.9 × 58.0 min of arc), referred to as the "dot-free zone". The fixed set was presented continually throughout a trial, whereas the adjustable set was flashed for a duration of 100 msec at a frequency of five times per minute, only while the observer pressed a button on a control box. At each presentation, the horizontal position of one of the two adjustable Nonius lines was controlled by the observer, via a joystick. Which of the two lines was controllable by the joystick on a given presentation was determined by the observer by pressing one of two buttons on a control box. The vertical distance between the centre of the fixed Nonius set and that of the adjustable set was 37.7 min of arc.

Procedure. Before beginning a trial, observers were asked if the two vertical lines of the fixed Nonius stimuli in the outer area appeared collinear. If they did not appear collinear, a set of variable prisms positioned in front of the observer's eyes were adjusted until they did appear collinear. Next, while fixating on the middle of the fixed Nonius stimuli, observers reported whether the inner area appeared to be in front of, behind, or on the same depth plane as the outer area. They then pressed the button on the control box to present the two red lines of the adjustable Nonius set and adjusted the horizontal position of one them, via the joystick, until it appeared collinear with the fixed Nonius stimuli. This presentation and adjustment sequence continued until both adjustable Nonius lines appeared collinear with the fixed Nonius lines. It was emphasized to the observers that the lines should be adjusted only when the two lines of the fixed Nonius stimuli appeared collinear.

Each observer completed a total of 54 trials, performed in six blocks of nine trials each. Within each block the

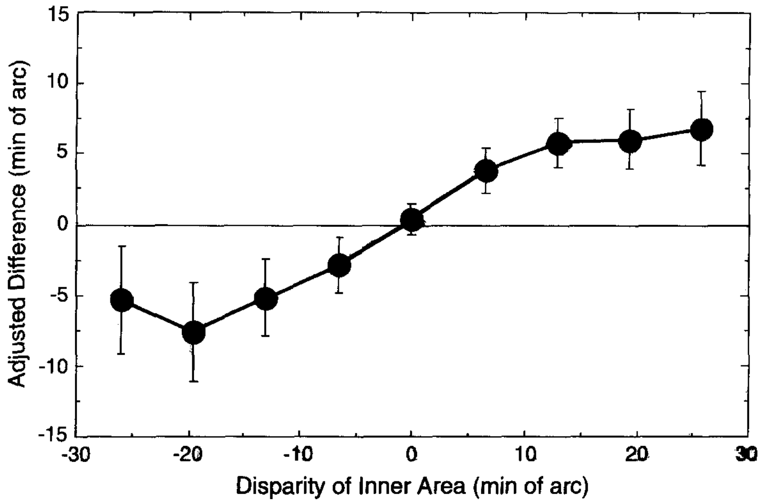

FIGURE 3. The mean adjusted difference of the adjustable Nonius lines and its standard error as a function of the disparity of the inner area of the stereogram in Experiment 1. Positive values represent crossed disparities and negative values uncrossed disparities.

stereogram was presented once at each of the nine different disparities. The presentation order within each block was randomized.

Results and discussion

The mean results from the eight observers are presented in Fig. 3. The ordinate, labeled the "adjusted difference" in the figure, represents the difference in the visual line values of the two adjustable Nonius lines when both sets of Nonius lines (the adjustable set and the fixed set) appeared aligned. This value is computed easily if it is assumed that fixation was on the stimulus plane. Without this assumption, however, the value is equal to the signed difference in the two eyes, of the differences in the horizontal positions of the adjusted Nonius lines and the fixed Nonius lines, when both sets of Nonius lines appeared aligned. Since an adjusted difference of zero indicates accuracy, Fig. 3 clearly shows that the Nonius method is inaccurate when the absolute value of the disparity of the stereogram is greater than zero.

A one-way, repeated measures analysis of variance was performed on the data, using the mean adjusted difference of the six settings for each observer, at each of the nine inner area disparity values, as the basic unit of the analysis. The analysis showed that the adjusted differences covaried with the disparity of the stereogram, $F(8,56) = 18.9$, $P < 0.001$. These mean adjusted differences were also used to compute the slope of each observer's regression line. Two regression lines were computed for each observer—one using the data from all nine disparity conditions, and the other using the data from only the five middle disparity conditions which were more linear. The means (and standard deviations) of the slopes for the eight observers were 0.31 (0.13) and 0.44 (0.15) for the nine-point and five-point analyses, respectively. Both of these slopes were significantly greater than zero, $t(7) = 6.12$, $P < 0.001$ and $t(7) = 7.23$, $P < 0.001$, for the nine-point and the five-point analyses, respectively.

Our finding that the adjusted difference of the adjustable Nonius lines covaried with the disparity of the stereogram suggests a reason for the inaccuracy of the Nonius method. It suggests that the visual system treats each of the two monocular Nonius lines as a part of its respective disparate binocular stimulus and, thus, transforms its visual line value when transferring it to the cyclopean eye. (See Ono *et al.*, 1997 for a discussion of transformation.) If the visual line values of the Nonius lines are transformed by the same extent as those of the binocular stimuli, then the adjustable Nonius lines will appear aligned when their adjusted difference equals the disparity of the stereogram. This was not the case, however, because the adjusted differences did not match the disparities of the stereogram exactly. This suggests that the extents of the transformations for the monocular Nonius stimuli were not the same as those for the binocular stimuli. Another way to describe this is that the "averaging" process discussed in Ono & Mapp (1995) was not "complete" for the monocular Nonius stimuli or that the shifts of the visual line values of the monocular Nonius stimuli were not as large as those for the binocular stimuli. (For a discussion of "averaging" being incomplete for binocular stimuli or "partial fusion", see Werner, 1937; Charnwood, 1951; Sperling, 1970; cf. Kaufman, 1976.) These ideas are discussed further in Experiments 2 and 3, and are similar to the idea of Erkelens & van Ee (1997a) that "monocular objects are assigned binocular visual directions that lie in between those of neighbouring binocular objects" (p. 1194).

The mean and standard deviation of the probable errors (or JND) for each of the five disparity values are presented in Table 1. The data from the crossed and uncrossed disparity conditions were combined, thereby, increasing the sample size to 12 trials per observer per disparity value, except for the zero disparity condition. [The probable errors were derived by multiplying the standard deviation value by the constant, 0.6745. The interval defined by plus and minus this value contains

TABLE 1. Mean (M) and standard deviation (SD) of the probable error (in min of arc) for each disparity value of the stereogram in Experiment 1 ($n = 8$)

		Disparity (min of arc)			
	Zero	6.5	13.0	19.4	25.9
M	0.90	1.17	1.16	1.23	1.26
SD	0.24	0.27	0.29	0.29	0.44

50% of the data, if they are normally distributed. Moreover, this value is theoretically equivalent to the JND (see Ono, 1993; Woodworth & Schlosberg, 1954).] The mean probable error was approximately equal in all conditions except for the zero disparity condition, in which it was somewhat smaller. A one-way, repeated measures analysis of variance performed on the data revealed a significant difference among the disparity conditions, $F(4,28) = 3.495$, $P < 0.05$. The *post hoc* analyses (Tukey test) showed that the mean in the zero disparity condition was significantly smaller than those in the 19.4 and the 25.9 min of arc disparity conditions.

These statistically significant results suggest that when the adjustable Nonius lines were seen in a different depth plane than the fixed Nonius lines, the observers' adjustments were less precise. Moreover, comparing the precision in the zero disparity condition with that reported by McKee & Levi (1987), indicates that embedding the Nonius stimuli in a random-dot stereogram also had a small adverse effect on the precision. If we assume that the probable error is equal to the JND, then our zero disparity condition precision value of 0.9 min of arc is slightly higher the 0.7 min of arc value reported by McKee & Levi (1987). An alternative explanation of this slight difference in precision, is that in our experiment the adjustable Nonius lines were presented below the fixation point, whereas in McKee & Levi's (1987) study they were presented on the fixation point.

In conclusion, the results clearly show that the Nonius method, although relatively precise, does not always reflect binocular eye position accurately. If one were to apply the laws of visual direction, stated in the Introduction, to the positions of the adjusted and the fixed Nonius lines, one would conclude that the eyes were converged to two different distances simultaneously. This, of course, is impossible and clearly demonstrates that visual line values do not always transfer to the cyclopean eye unaltered and, therefore, the Nonius method does not always reflect binocular eye position accurately. The methodological implication of these results is clear. The Nonius method should be avoided in these types of stimulus situations, because the perceived directions of monocular Nonius lines presented adjacent to binocular stimuli, are not predictable from the laws of visual direction.

EXPERIMENT 2

Experiment 2 was designed to demonstrate that changes in vergence angle are not always detected by the Nonius method. To demonstrate this, we looked for a stimulus condition in which two sets of apparently aligned Nonius stimuli, which appeared at two different depths, continued to appear aligned as they were fixated alternately. (In a preliminary study, we found that with the stereograms used in Experiment 1, changing fixation from one set of Nonius stimuli to the other caused the non-fixated set to appear misaligned.) Once this condition was found, we monitored binocular eye position objectively to determine the magnitude of the vergence eye movement accompanying the change in fixation from one set of apparently aligned Nonius stimuli to the other.

Method

Observers. Three male students from the university community, ranging in age from 19 to 32 years, participated. All reported having normal or corrected to normal visual acuity and stereopsis. Two of the three observers (TS and KY) were experienced in eye movement experiments, and all three were naïve as to the purpose of the experiment.

Stimuli and apparatus. The apparatus consisted of the mirror stereoscope and the eye-movement recording system used in Ono *et al.* (1997). The stereoscopic images were presented on two colour monitors (NEC PC-KD853), each of which was driven by its own computer (NEC PC-9801). The centres of the monitors were set at eye level, at an optical distance of 100 cm from the corneal plane.

As in Experiment 1, the stimulus consisted of a random-dot stereogram, in which were embedded two sets of Nonius stimuli. The stereogram was composed of a pair of square areas (one presented to each eye), of 80 × 80 picture elements each. The inner area of each half of the stereogram consisted of a square area of 40 × 40 picture elements. Each of the picture elements subtended 2.6 × 2.6 min of arc. With respect to the outer area, the inner area was presented with either no disparity or with a crossed or uncrossed disparity of 5.2 or 10.4 min of arc. One of the two sets of Nonius stimuli, the upper set, was embedded in the outer area of the stereogram, and the other, the lower set, was embedded in the inner area. Each Nonius stimulus consisted of a horizontal line (31.2 × 5.2 min of arc) and a vertical line (5.2 × 10.4 min of arc) for each eye. The vertical distance between the centres of the two Nonius sets was 31.2 min of arc. The upper set was fixed at the horizontal centre of the outer area, and the lower set was adjustable. The colour of the stereogram and that of the Nonius stimuli were bright purple and white, respectively. The colours differed from those used in Experiment 1, because one of the observers reported that the red Nonius stimuli in the white space, used in Experiment 1, disappeared sometimes, whereas the white Nonius stimuli in the purple space appeared continuously.

Binocular eye movements were monitored using a photo-electric method, and were recorded on an analog data recorder (Sony Instrumentation KS-616). This

TABLE 2. Mean (M) and standard deviation (SD) of the adjusted difference of the lower Nonius lines (in min of arc) for the stereograms with zero, crossed and uncrossed disparities in Experiment 2 ($n = 4$)

	Stereogram					
	Zero		Crossed disparity		Uncrossed disparity	
Observer	M	SD	M	SD	M	SD
YY	0.00	0.00	4.88	0.65	−4.88	0.65
KY	0.33	0.65	0.98	0.65	−5.20	0.00
TS	0.00	0.00	1.63	1.64	−4.88	0.65

Note: Positive values represent crossed disparities and negative values uncrossed disparities.

system measured horizontal eye movements linearly in the range of approximately 6 deg, with a resolution of 2.0 min of arc when the band width was limited from 0 to 100 Hz. Before each session, the system was calibrated by having observers fixate alternately on two stimuli, separated horizontally by 67 min of arc, for 3–5 sec.

Procedure. First, we determined which of the four stereograms (5.2 or 10.4 min of arc, crossed or uncrossed disparities), met the criterion that both sets of Nonius stimuli continued to appear aligned as they were fixated alternately. Thus, the four stereograms were presented in random order, and the observers were asked to (a) adjust the horizontal position of the lower Nonius stimuli until they appeared aligned, while fixating on and maintaining alignment of the upper Nonius stimuli as in Experiment 1; and (b) indicate whether the upper Nonius stimuli continued to appear aligned when the lower Nonius stimuli were fixated and appeared aligned. The 5.2 min of arc disparity stereograms (crossed and uncrossed) met the criterion and, therefore, were used in the objective eye movement recording sessions described below.

Next, for each of the stereograms which met the criterion (5.2 min of arc with crossed and uncrossed disparities) and for a stereogram with zero disparity, each observer readjusted the lower Nonius lines to appear aligned, while maintaining fixation on and alignment of the upper Nonius lines, four times. The presentation order of the three stereograms was randomized and differed for each observer. The mean adjusted difference obtained from each stereogram condition was used to determine the disparity of the lower Nonius stimuli, with respect to the upper Nonius stimuli, to be used in the objective eye movement recording sessions.

Finally, binocular eye movements were recorded objectively in three sessions; one for the crossed disparity stereogram, one for the uncrossed disparity stereogram, and one for the zero disparity stereogram. In each session, the observers were instructed to (a) change fixation from one of the two sets of aligned Nonius stimuli to the other, in synchrony with the change in pitch of a sound generated by a function generator (NF model FG-143); and (b) push a button on a control box if either one of the two sets of Nonius stimuli no longer appeared aligned. The sound's pitch was changed from 270 to 1180 Hz every 5 sec, and the observers were asked to fixate the lower or the upper Nonius stimuli, when they heard the lower or the higher pitches, respectively.

Results and discussion

The means and standard deviations of the four adjusted differences, in each of the stereogram conditions, are shown in Table 2. These means were used to determine the horizontal disparities of the lower Nonius stimuli with respect to the upper Nonius stimuli that were used in the objective eye movement recording sessions. For the 5.2 min of arc crossed disparity stereogram, the horizontal disparity of the Nonius lines was set at 5.2 min of arc, for all observers. (The transformation of the monocular visual line values in this instance corresponds to that of the disparate binocular dots in the stereogram. Evidently, the "averaging" is complete for a monocular stimulus placed in a stereogram with a very small crossed disparity.) For the 5.2 min of arc uncrossed disparity stereogram, the horizontal disparity of the Nonius lines was set differently for the different observers. For observers KY and TS, it was set at 1.3 min of arc and for observer YY it was set at 5.2 min of arc. In the control condition (zero disparity stereogram), the horizontal disparity of the Nonius lines was set at zero, for all observers.

With the horizontal disparity values specified above, all three observers reported that both sets of Nonius lines continued to appear aligned throughout all of the objective eye movement recording sessions. Thus, any changes in vergence angle detected by the eye movement monitor were not detected by the Nonius method.

The eye position data were analyzed as follows. First, the eye position records were sampled and digitized every 10 msec using Maclab/8. Next, records containing eye blinks were eliminated and the difference between the left and right eye positions was computed to indicate binocular eye position, (see Ono, 1983, for a discussion of this technique). Following this, the usable records (the exact numbers are shown in Table 3) were averaged to increase the signal-to-noise ratio, and the difference between the averaged binocular eye positions in the control condition and those in each of the disparity conditions was computed and used as an index of vergence position. (However, for the crossed disparity stereogram, vergence movements of two observers, KY,

TABLE 3. Mean (M) and standard deviation (SD) (in min of arc) of the differences in averaged binocular eye positions before and after the signal to change fixation, for the control, the crossed disparity, and the uncrossed disparity conditions in Experiment 2

	Conditions								
	Control			Crossed disparity			Uncrossed disparity		
Observer	M	SD	n	M	SD	n	M	SD	n
YY	4.82	4.62	8	9.94	5.61	15	−0.37	3.89	13
KY	0.89	4.37	7	—	—	—	−5.83	6.15	13
TS	4.24	4.76	9	—	—	—	−2.34	3.51	9

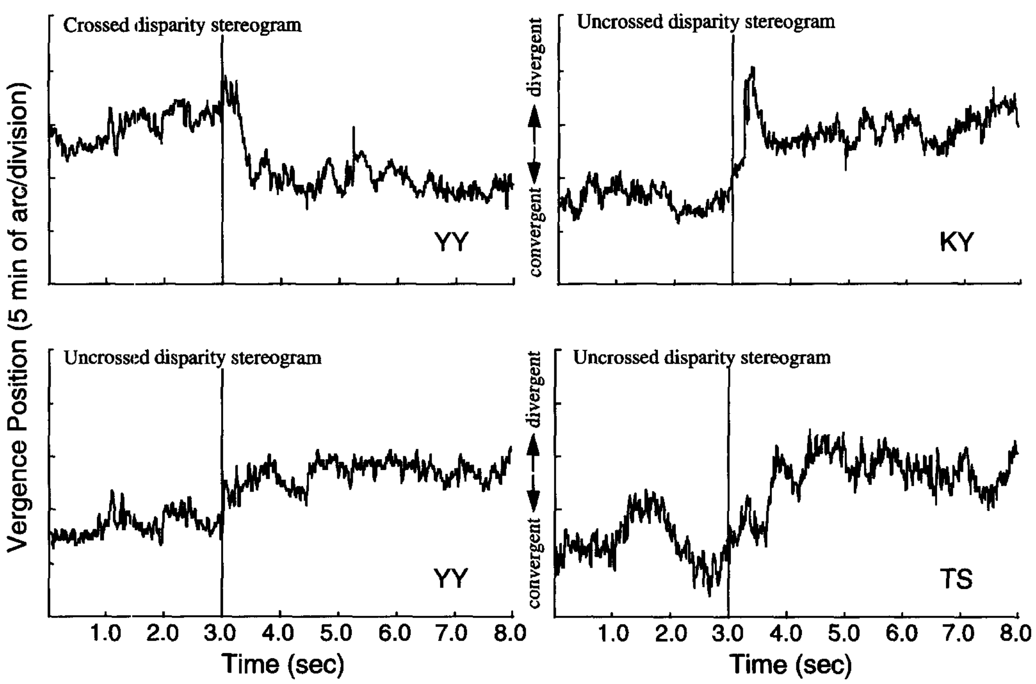

FIGURE 4. The averaged eye-movement traces when observers fixated the upper and lower Nonius sets alternately, for the stereograms with crossed and uncrossed disparities. See text for details.

and TS, are not reported, because analyses indicated that their change in binocular eye position could not be discriminated from the noise in the record.) The observers' average vergence positions during the period 3 sec before and 5 sec after the signal to change fixation from the upper to the lower Nonius stimuli are presented in Fig. 4.

The figure clearly shows that vergence eye movements took place. For all three observers, the change in fixation resulted in a change in vergence position, and its direction was consistent with the disparity of the stereogram (i.e., the vergence angles increased or decreased for the crossed or uncrossed disparity stereograms, respectively). Moreover, for all three observers the change in binocular eye position in the crossed and uncrossed disparity conditions differed significantly from that in the control condition. Table 3 presents the mean differences in averaged binocular eye positions before and after the signal to change fixation for the control, the crossed, and the uncrossed disparity conditions. The values in the table were derived by subtracting the mean binocular eye position during the 3-sec period, 2 sec following the signal to change fixation, from the mean binocular eye position during the 3-sec period immediately preceding the signal to change fixation. The mean from the control condition was statistically significantly different from that of the crossed disparity condition, $t(21) = 2.21$, $P < 0.05$, and that of the uncrossed disparity condition, $t(19) = 2.74$, $P < 0.002$, for observer YY. Also, the mean from the control condition was significantly different from those of the uncrossed disparity conditions, $t(18) = 2.55$, $P < 0.05$ and $t(16) = 3.34$, $P < 0.001$, for observers, KY and TS, respectively.

To determine the magnitude of the change in vergence angle we subtracted the mean binocular eye positions for the crossed and uncrossed disparity conditions, presented in Table 3, from that of the control condition. For the crossed disparity condition, the change in vergence angle was 5.1 min of arc for observer YY, and for the uncrossed disparity condition it was 5.2, 6.7, and 6.6 min of arc for observers YY, KY, and TS, respectively. The mean change in vergence angle, collapsed across observers and disparity conditions, was 5.9 min of arc, which agrees well with the 5.2 min of arc disparity of the stereogram. The results clearly show that changes in vergence angle of up to approximately 6 min of arc are not detected by the Nonius method when the Nonius stimuli are embedded in a random-dot stereogram. This failure of the Nonius method to detect a change in vergence angle, in this stimulus situation, is probably because: (a) the retinal displacement is small; and (b) the transformation of the visual line values match that of the surrounding area. That is, with the stimulus we used the two lower Nonius lines appeared aligned when their adjusted difference (their horizontal disparity) was equal to the disparity of the inner area of the stereogram, relative to the outer area. Thus, just as the retinal displacement (or motion) of the inner area is "compensated" for or "taken into account" by the vergence eye movement (see e.g., Erkelens & Collewijn, 1985), the displacement of the monocular lines are also compensated. If, however, the extents of the transformations of the Nonius lines and the random dots are not the same, as with the 10.4 min of arc disparity stereogram, then the apparent alignment is no longer maintained when the vergence angle changes.

The methodological implication of these results is clear; the Nonius method should not be used to detect binocular eye movements when the Nonius lines are placed in random-dot stereograms with small disparity.

EXPERIMENT 3

Experiments 1 and 2 clearly show that the Nonius method cannot be used to monitor binocular eye position or to detect binocular eye movements, in all stimulus situations. Moreover, the results of these two experiments, as well as those reported by Ono *et al.* (1997) and by Erkelens & van Ee (1997a,b), suggest that the situations in which the Nonius method cannot be used are those in which monocular Nonius stimuli are positioned in close proximity to surrounding binocular stimuli. This is so, because in these situations the visual line values associated with the Nonius stimuli do not transfer unaltered to the cyclopean eye. Thus, Experiment 3 was designed to determine if there are stimulus situations in which the visual line values of monocular Nonius stimuli, surrounded by binocular stimuli, are transferred unaltered to the cyclopean eye. Defining such stimulus situations is important, for it is only in these situations that the Nonius method can be used to monitor binocular eye position.

Method

Observers. Eleven members of the university community, one female and 10 males ranging in age from 18 to 39 years, participated. All reported having normal or corrected to normal visual acuity and stereopsis.

Stimuli and apparatus. The apparatus, with the exception of the computer and monitor, was the same as that used in Experiment 1. The computer (NEC PC-9801) used to generate the stimuli and the monitor (NEC PC-KD853) used to display them, were the same as those used in Experiment 2.

As in Experiments 1 and 2, the stimulus consisted of a random-dot stereogram in which were embedded two sets of Nonius stimuli. The stereogram was composed of a pair of rectangular areas (one presented to each eye) of 64 × 60 picture elements each. The inner area of each half of the stereogram consisted of a rectangular area of 50 × 30 picture elements. Each of the picture elements subtended 5.2 × 5.2 min of arc. With respect to the outer area, the inner area was presented with either no disparity or with crossed or uncrossed disparities of 10.4 or 20.8 min of arc. One of the two sets of Nonius stimuli, the fixed set, was embedded in the outer area of the stereogram and the other, the adjustable set, was embedded in the inner area. The fixed set consisted of a pair of horizontal lines (41.6 × 5.2 min of arc) and a pair of vertical lines (5.2 × 10.4 min of arc). The vertical lines were fixed at the horizontal centres of the outer areas. The adjustable set was presented in a dot-free zone (1.0 deg high × 1.1, 2.2, 3.3, or 4.3 deg wide) located in the upper middle portion of the inner area of each half of the stereogram, and consisted of a pair of vertical red lines (5.2 × 11.7 min or arc) separated vertically by 3.9 min of arc. The horizontal position of the adjustable set was controlled by the observer via two keys on a keyboard. The fixed set was presented continually throughout a trial, whereas, the adjustable set was flashed for a duration of 100 msec and at a frequency of five times per minute, only while the observer pressed a key on the keyboard. The vertical distance between the centre of the fixed Nonius set and that of the adjustable set was 31.2 min of arc.

Procedure. The procedure was essentially identical to that of Experiment 1. Namely, observers adjusted the horizontal position of the adjustable Nonius stimuli until they appeared collinear, while maintaining fixation on the fixed Nonius stimuli, which continued to appear collinear throughout the trial. What differed from Experiment 1 is that the experimenter varied the width of the dot-free zone in which the adjustable Nonius stimuli were presented.

Each observer completed a total of 40 trials, performed in five blocks of eight trials each. Within each block, stereograms of one of the five disparities were presented twice, with each of the four different widths of the dot-free zone. The presentation order within each block was randomized, and the order of the blocks was varied between observers.

Results and discussion

The mean results from the 11 observers are presented in Fig. 5. As in Experiment 1, the adjusted difference (i.e. the dependent variable) refers to the difference in the visual line values of the two adjusted Nonius lines. The width of dot-free zone (i.e. the independent variable) refers to the width of the white space within which the adjustable Nonius lines were presented. The figure clearly shows that as the width of the zone increased, the absolute value of the adjusted difference decreased. In other words, as the horizontal distance between the monocular Nonius lines and the binocular random dots was increased, the magnitude of the transformation of the Nonius lines' visual line values decreased.

We performed a two-way, repeated measures analysis of variance on the data (5 stereogram disparities × 4 widths of the dot-free zone) using the mean adjusted difference of the two settings for each observer, at each of the four zone widths as the basic unit of the analysis. The analysis showed that the main effect of disparity and the interaction between disparity and dot-free zone width were statistically significant, $F(4,40) = 17.74$, $P < 0.001$ and $F(12,120) = 6.31$, $P < 0.001$, respectively. The main effect of dot-free zone was not statistically significant, $F(3,30) = 0.44$, $P > 0.05$. The mean adjusted differences were also used to compute five regression lines for each observer as a function of the width of the dot-free zone; one for each of the five different disparity values of the stereogram. These values are presented in Table 4. For all but the zero disparity condition, the slopes were significantly different from zero; $t(10) = -5.23$, $P < 0.001$, $t(10) = -2.83$, $P < 0.05$, $t(10) = 3.01$, $P < 0.05$, $t(10) = 3.06$, $P < 0.05$, for the 10.4′ crossed, 20.8′ crossed, 10.4′ uncrossed, and 20.8′ uncrossed disparity conditions, respectively. These results clearly

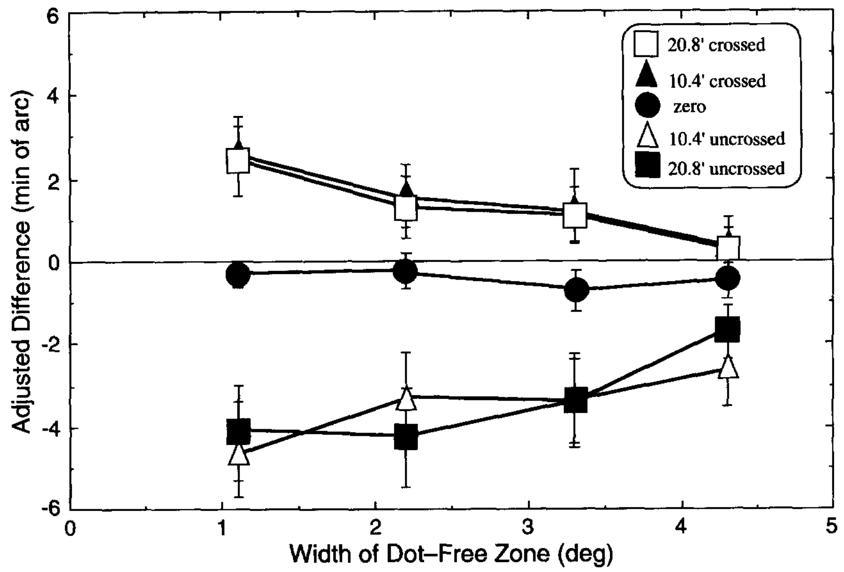

FIGURE 5. The mean adjusted difference and its standard error as a function of the width of the dot-free zone in the five stereogram disparity conditions of Experiment 3. Positive values represent crossed disparities and negative values uncrossed disparities.

TABLE 4. Mean (M) and standard deviation (SD) of the slope of the adjusted differences as a function of the width of the dot-free zone in Experiment 3 ($n = 11$)

	Disparity conditions				
	28.8′ uncrossed	10.4′ uncrossed	Zero	10.4′ crossed	20.8′ crossed
M	0.55	0.76	−0.10	−0.62	−0.63
SD	0.60	0.84	0.27	0.39	0.73

support the idea that as the horizontal distance between the monocular Nonius stimuli and the binocular stimuli increases, the validity of the Nonius method increases.

The results from this experiment suggest that Nonius stimuli can be used to monitor binocular eye position if they are not positioned in close proximity to surrounding disparate binocular stimuli. With the widest dot-free zone (4.3 deg), the mean adjusted differences of the adjustable Nonius lines were not significantly different from zero, for the 10.4 and the 20.8 min of arc crossed disparity stereograms, $t(10) = 0.60$, $P > 0.10$, and $t(10) = 0.42$, $P > 0.10$, respectively. This non-significance is consistent with the assumption of the Nonius method that the visual line values of the monocular Nonius stimuli are transferred unaltered to the cyclopean eye. Thus, in these conditions, the Nonius alignment reflected the eye position. On the other hand, the mean adjusted differences were significantly different from zero at the widest dot-free zone for the 10.4 and the 20.8 min of arc uncrossed disparity stereograms, $t(10) = 2.64$, $P < 0.05$, and $t(10) = 2.65$, $P < 0.05$, respectively. These significant differences do not necessarily contradict the argument presented above, however, because even in the uncrossed disparity conditions, the accuracy of the Nonius method improved as the width of the dot-free zone increased. Thus, it is likely that if we had increased the width of the dot-free zone even further, the Nonius alignment would have reflected vergence position accurately in the new subcondition of the uncrossed disparity conditions as well.

Our argument that the Nonius method can reflect vergence position accurately when the dot-free zone is large is supported by a recent finding of Erkelens & van Ee (1997b). Although their experimental paradigm (observers viewed a monocularly presented line embedded in a random-dot stereogram in which the half-images oscillated in counterphase) and their terminology differ from ours, their findings are consistent with those reported here. Namely, as the horizontal separation between monocular and binocular objects increases, the extent of the transformation of the monocular objects' visual line values (our terminology), or the degree of capture of the visual directions of the monocular objects (Erkelens and van Ee's terminology), decreases.

GENERAL DISCUSSION

When can the Nonius method not be used to monitor binocular eye position or binocular eye movements? The answer to this question can be found in the results of Experiments 1 and 2, where the principles of visual direction were violated. When Nonius stimuli are positioned in close proximity to the binocular elements in a random-dot stereogram, the visual system treats them as disparate binocular stimuli, and transforms their visual line values when transferring them to the cyclopean eye. Moreover, the extent of this transformation is dependent on the disparity of the stereogram within which they are embedded. With small disparity stereograms (less than 5.2 min of arc) the extent of the transformation is equal to that of the binocular elements in the stereogram, and with large disparity stereograms the extent of the transformation is less than that of the binocular elements in the stereogram. Therefore, the Nonius method cannot be used to monitor binocular eye position when the Nonius stimuli are positioned in close proximity to binocular stimuli. Moreover, it cannot be used to detect binocular eye movements when the Nonius stimuli are positioned in close proximity to binocular stimuli in a small disparity stereogram.

When can the Nonius method be used to monitor binocular eye position? The answer to this question can be found in the results of Experiment 3. When Nonius stimuli are presented in a way that precludes the visual system from treating them as disparate binocular stimuli, they are treated as monocular stimuli and their visual line values are transferred unaltered to the cyclopean eye. The way in which we disassociated the Nonius stimuli from the binocular elements of the stereograms in Experiment 3 was by presenting them in a white area, devoid of any binocular elements. When this dot-free area was large enough, the visual system ceased treating the Nonius stimuli as disparate binocular stimuli, and transferred their visual line values unaltered to the cyclopean eye. Therefore, the Nonius method can be used to monitor binocular eye position when the Nonius stimuli are disassociated from the binocular elements of the stereogram.

In conclusion, the Nonius method, although not as universally useful as originally thought, can still be used to monitor binocular eye position accurately and precisely. When using this method, however, one must take care to ensure that the visual line values associated with the Nonius stimuli are transferred unaltered to the cyclopean eye. One way of ensuring this is to spatially separate the Nonius stimuli from the binocular elements of the stimulus, as we did in some of the conditions in Experiment 3. The extent of the required separation, however, may differ depending on the characteristics of the binocular elements of the stimulus. Another way is to temporally separate the Nonius stimuli from the binocular elements of the stimulus and then flash the binocular elements by themselves, immediately after a Nonius alignment.

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