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Capture of visual direction in dynamic vergence is reduced with flashed monocular lines ☆

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Abstract

The visual direction of a continuously presented monocular object is captured by the visual direction of a closely adjacent binocular object, which questions the reliability of nonius lines for measuring vergence. This was shown by Erkelens, C. J., and van Ee, R. (1997a,b) [Capture of the visual direction: An unexpected phenomenon in binocular vision. Vision Research, 37, 1193–1196; Capture of the visual direction of monocular objects by adjacent binocular objects. Vision Research, 37, 1735–1745] stimulating dynamic vergence by a counter phase oscillation of two square random-dot patterns (one to each eye) that contained a smaller central dot-free gap (of variable width) with a vertical monocular line oscillating in phase with the random-dot pattern of the respective eye; subjects adjusted the motion-amplitude of the line until it was perceived as (nearly) stationary. With a continuously presented monocular line, we replicated capture of visual direction provided the dot-free gap was narrow: the adjusted motion-amplitude of the line was similar as the motion-amplitude of the random-dot pattern, although large vergence errors occurred. However, when we flashed the line for 67 ms at the moments of maximal and minimal disparity of the vergence stimulus, we found that the adjusted motion-amplitude of the line was smaller; thus, the capture effect appeared to be reduced with flashed nonius lines. Accordingly, we found that the objectively measured vergence gain was significantly correlated ($r = 0.8$) with the motion-amplitude of the flashed monocular line when the separation between the line and the fusion contour was at least 32 min arc. In conclusion, if one wishes to estimate the dynamic vergence response with psychophysical methods, effects of capture of visual direction can be reduced by using flashed nonius lines.

Keywords: Binocular visual direction; Vergence; Eye movements; Nonius lines

1. Introduction

In monocular vision, the perceived direction of an object is specified by the geometry describing the position of the object and the eye: each retinal location is associated with a certain visual direction. These rules for monocular vision were traditionally expected to be also valid for monocular objects that are presented combined with binocular objects, since Wells-Hering's laws of visual direction state that the visual directions of the right and left eye are transferred unaltered to the cyclopean eye (Howard & Rogers, 2002). According to these rules, the vergence angle between the visual axes of the two eyes can be measured psychophysically (i.e., subjectively) from the perceived misalignment of two physically aligned monocular objects that are presented separately to the two eyes; typically two dichoptic nonius lines are used (Shimono, Ono, Saida, & Mapp, 1998).

However, research has shown that the rules of visual direction are violated in particular conditions, as summarized by Howard and Rogers (2002). One of these conditions refers to dynamic vergence eye movements. Erkelens and van Ee (1997a, 1997b) presented a random-dot fusion target that moved sinusoidally in counter phase in each eye by ±40 min arc at a frequency of 0.75 Hz (Fig. 1); this dynamic target appeared stationary during vergence eye

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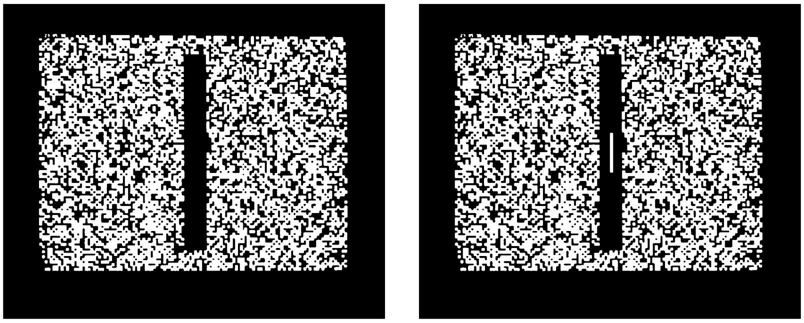

Fig. 1. Random-dot patterns that were presented to the right and left eye, respectively, and moved in counter phase to induce periodical vergence eye movements. The patterns contained a centre dot-free gap of constant height (20 deg), the gap width was 16, 44, 80, or 144 min arc in different experimental conditions. A vertical line (4 deg high and 16 min arc wide) was centered in the gap of either the right or the left eye. This line moved horizontally with the same frequency and phase as the corresponding random-dot pattern; the motion-amplitude of the line was adjusted until the line appeared as (nearly) stationary. In Experiment 1, the size of the random-dot patterns was 40 × 40 deg and in Experiment 2 it was 30 × 24 deg (horizontal × vertical); the latter is shown in this figure.

movements. In a centre dot-free gap of the random-dot target, they presented a continuously visible monocular line that moved in phase with the fusion stimulus in one eye, while subjects adjusted the motion-amplitude so that the line appeared stationary. When the gap was narrow, this adjusted motion-amplitude of the line was the same as that of the fusion target (±40 min arc). This would mean perfect vergence eye movements, provided the line were a valid vergence indicator. Since large vergence errors were observed in this condition, the stationary perception of both the random-dot pattern and the monocular line (when both move with a ±40 min arc amplitude) means that a continuously presented monocular line (adjacent to a fusion contour) received the visual direction of the fusion stimulus, or—in other words—the line is represented as part of the binocular random-dot pattern, irrespective of the actual vergence errors. This effect of capture of visual direction gradually declined with increasing separation between monocular line and fusion contour.

Thus, Erkelens and van Ee (1997a, 1997b) and further research reviewed by Howard and Rogers (2002) have identified conditions where the laws of visual directions are invalid, i.e., monocular lines do not measure the vergence angle in dynamic vergence or do not indicate the visual direction in stereograms. However, other studies suggest that capture of visual direction seems not to play a role in all conditions where monocular lines are used for measuring vergence. A stationary fusion stimulus in a single depth plane is an important condition in clinical testing the vergence system, e.g., for measuring fixation disparity (Evans, 2002; Mallett, 1974). Two studies varied the separation between a stationary fusion stimulus and the nonius lines to investigate possible modification of the subjectively measured fixation disparity (as predicted by capture of visual direction). However, Ukwade (2000)—using flashed nonius lines—did not find a change in fixation disparity up to a separation of 0.6 deg. Similar, Jaschinski, Kloke, Jainta, and Buchholz (2005) did not find a change up to a separation of about 3.3 deg (neither with flashed nor with continuous nonius lines); at larger separations, changes in fixation disparity occurred with flashed nonius lines in some subjects, but the nature of this effect differed from capture of visual direction.

Further, Popple, Findlay, and Gilchrist (1998) flashed nonius lines for 160 ms following a 230 ms vergence step stimulus by changing the absolute disparity of a fusion stimulus: they found good agreement between nonius results and objective vergence eye movement recordings and concluded that “alignment of nonius flashed subsequently to a stimulus provides a reliable measure of vergence.” Dichoptic nonius lines flashed after a step stimulus were used in several studies and provided physiologically plausible results (e.g., Fredenburg & Harwerth, 2001; Jaschinski, 2004; Mallot, Roll, & Arndt, 1996; Popple, Smallman, & Findlay, 1998b).

Thus, on the one hand some studies found valid estimations of vergence with flashed nonius lines (even in conditions of vergence dynamics) while—on the other hand—studies reporting on capture of visual direction used monocular lines that were continuously visible. Therefore, we investigated in the present study whether the capture effect might be absent or reduced if a monocular line is presented in a series of short flashes. We expected that the process of transferring the visual direction from the fusion stimulus to the monocular line might require a certain amount of time; thus, capture might not occur, if the monocular line is presented for a shorter period only. A possibility to separate the fusion stimulus and the monocular line temporally was mentioned by Shimono et al. (1998).

Thus, we applied the dynamic vergence paradigm of Erkelens and van Ee (1997a, 1997b) to test whether capture of visual direction might be reduced with a flashed monocular line (Experiment 1) which may allow for subjective vergence measures that are correlated with the objectively measured vergence response (Experiment 2).

2. Methods

2.1. Subjects

In Experiment 1, the six subjects were experienced in visual experiments and familiar with the aims of the study; they used trial lenses to correct for ametropia (and presbyopia in one case). In Experiment 2, we had young adult emmetropic subjects with a visual acuity of 1.0 or better in each eye and an accommodative power of 4 dioptre without needing glasses, which was essential for eye movement recordings. For the intended correlation between vergence measures, 28 subjects were recruited to cover the range of individual differences (see below for sub-samples). They were unaware of the aims of the study, but inexperienced in visual experiments.

2.2. Stimuli and apparatus

The absolute disparity of a fusion stimulus (Fig. 1) was temporally varied following a triangular-wave (Fig. 2). The fusion stimulus comprised two identical random-dot patterns (16 min arc square elements; 50% dot density) that moved horizontally in counter phase in the left and right eye with a amplitude of ±39.5 min arc and a frequency of 0.75 Hz (period of 1.33 s). Thus, the range of the vergence stimulus was 158 min arc or 2.6 deg. The fusion stimulus subtended 40 × 40 deg in Experiment 1 and was 30 deg wide and 24 deg high in Experiment 2. A central rectangular gap was free of random-dot elements. This gap was always 20 deg high, while the gap width was either 16, 48, 80, or 144 min arc. A monocular vertical line (240 × 16 min arc) was centered in the dot-free gap of either the right or the left eye and moved following a triangular-wave of the same frequency and phase as the random-dot pattern of the respective eye; the motion-amplitude was adjusted by the subject until the line appeared stationary or showed a minimal motion. Separate runs were made with the monocular line either presented continuously (i.e., the line was permanently visible) or flashed for 67 ms with a flash onset at the moments of maximal and minimal disparity of the vergence stimulus (Fig. 2).

We used a CRT monitor (Samtron 75PPLUS) and liquid crystal shutter glasses (Elsa, Revelator) for dichoptic separation; the frame rate was 120 Hz, i.e., each eye received images at a 60 Hz rate. In Experiment 1, we masked any residual cross-talk of the shutter glasses by using an elevated white background luminance of 5.5 cd/m^2 so that the stimulus contrast $(L_{\max} - L_{\min})/L_{\max}$ was reduced to 0.28. The fusion stimulus was white, the monocular line was white or green. In Experiment 2, all stimulus elements were red (2.5 cd/m^2) on a nearly black background (0.3 cd/m^2) since the shutter glasses have optimal dichoptic separation for red stimuli. The viewing distance was 30 cm in Experiment 1 and 53 cm in Experiment 2. A chin and forehead rest including a narrow temporal rest was used to minimize head movements.

2.3. Psychophysical procedures

We measured the physical motion-amplitude of the monocular line that resulted in minimal (if any) perceived motion of the monocular line. Subjects adjusted the motion-amplitude with the buttons of a computer mouse; the result was defined as the amplitude adjusted at the end of the trial of 30 s duration. In Experiment 1, the initially presented amplitude varied from trial to trial so that the (experienced) subjects were unaware of the actual motion-amplitude. This procedure had the disadvantage that subjects were uncertain whether to respond left or right to reduce the apparent motion. Therefore, in Experiment 2, a fixed initial motion-amplitude of 45.3 min arc was used and subjects were informed that—for initial adjustment—an apparent motion can be reduced by responding "right" (since all expected results are near 40 min arc or below). This procedure appeared to be justified since all subjects in Experiment 2 were unaware of the hypotheses.

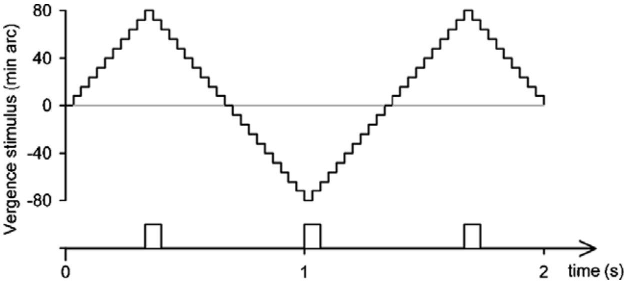

Fig. 2. Temporal triangular-wave of the counter phase motion of the random-dot patterns presented to the two eyes. The flashed monocular line was switched on for 67 ms at the moments of maximal and minimal disparity of the random-dot patterns.

2.4. Eye movement recordings and analysis

In Experiment 2, we measured eye movements with the IRIS-infrared reflection system (Skalar medical, Delft, The Netherlands) and sampled the signal at a rate of 2 ms. Each eye was calibrated separately, twice before and a third time after each trial of 30 s duration: a monocular fixation target (a vertical line with a central spatial gap) appeared randomly (for 1400 ms with 100 ms temporal gaps) at one of five positions: at the screen centre and at horizontal displacements of 95 or 190 min arc left or right.

Raw data may be invalid due to blinks or saccades, which were identified by screening whether data exceeded limits in either absolute value, first or second derivative; these were considered as missing values. With the raw data of all three calibrations, we determined linear calibration factors between locus of stimulus and measured raw data, separately for each eye. We used the function "rlm" from MASS statistics package (Ihaka & Gentleman, 1996; Venables & Ripley, 1999) which provides robust regressions to reduce the effect of blinks and artefacts: the data were iteratively weighted until convergence was reached. Trials where "rlm" did not converge and those with an unreasonably low calibration factor were discarded (30 of 638 trials available of all subjects).

This robust regression was also applied for the signal of each eye during the 30 s trials against sine and cosine of the first harmonic of the stimulus, from which amplitude and phase were computed. Vergence was defined as difference between the eyes in angular position and vergence gain as the relation between response and stimulus for the first harmonic (0.75 Hz) in the triangular-wave. The version component resulted from the mean of left and right eye position.

From the initial 28 subjects, seven were excluded after a preliminary session because they were very uncertain in judging the monocular line (four subjects) or eye movements could not be measured (three subjects). The 608 trials available of all subjects with valid calibrations gave a vergence gain of 0.44 ± 0.12 (means ± SD). Regarding this distribution, vergence gain values smaller than 0.15 and larger than 0.8 were discarded as invalid outliers (32 trials).

2.5. Experimental design, test conditions, and statistical analysis

We had eight experimental conditions: a continuous or flashed monocular line at each of the four gap widths. In Experiment 1, the session comprised one adjustment of the motion-amplitude in each of the following line conditions: the monocular line was either white or green and was visible by the right or left eye; the two latter results were averaged. In Experiment 2, the red monocular line was presented to the left eye; two sessions were made, each with at least one trial for each of the eight experimental conditions; a trial was repeated if many blinks or other artefacts deteriorated the eye movement recording during the calibration or 30 s trial period. Seventeen subjects had at least one valid eye movement trial in each experimental condition. The available trials per conditions (three on the average) were averaged for each subject. The adjusted motion-amplitude was statistically analyzed with a repeated measures ANOVA, based on the 17 individual mean values.

3. Results

Fig. 3 shows the mean adjusted motion-amplitude of the monocular line, when it was perceived as (nearly) stationary; the results of the monocular line in the right or left eye were averaged in Experiment 1. With the continuous line

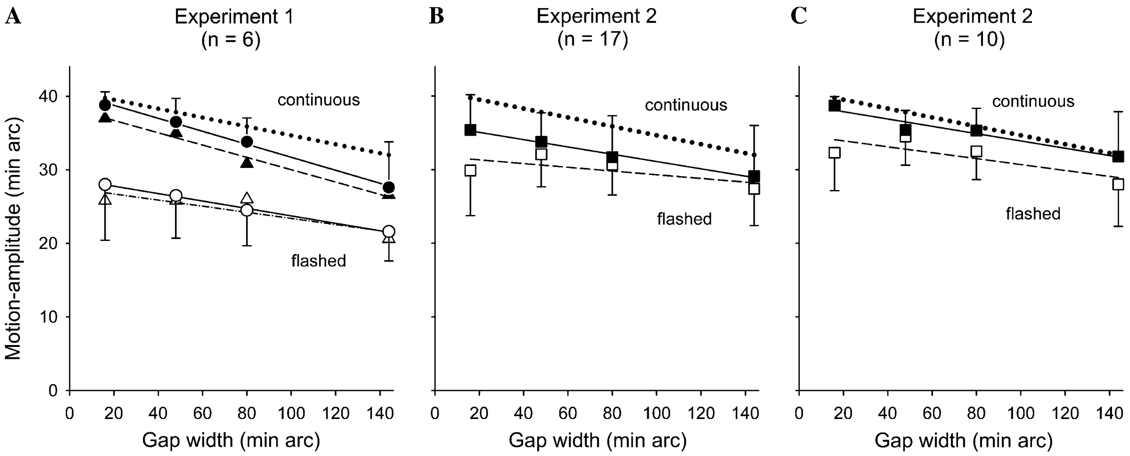

Fig. 3. Adjusted motion-amplitude (means ± SD) of the monocular line (continuous versus flashed, i.e., filled versus open symbols) as a function the gap width with regression lines. (A) Data of six subjects in Experiment 1: circles and triangles refer to a white and green monocular line, respectively. The fusion stimulus was always white. (B) Data of 17 subjects in Experiment 2 with red stimuli. (C) Data of the sub-sample of ten subjects in Experiment 2 who showed motion-amplitudes larger than 35 min arc with a continuous monocular line at the gap width of 16 min arc. (A–C) The dotted lines indicate the mean result of the four subjects in Erkelens and van Ee (1997b) for comparison.

and the smallest gap width of 16 min arc, most subjects adjusted a motion-amplitude that nearly reached the full disparity stimulus of ±39.5 min arc (particularly in Experiment 1). The individual settings were larger than 35 min arc in all subjects of Experiment 1 (Fig. 3A) and in 10 of 17 subjects of Experiment 2 (Fig. 3B). As the gap width increased, the adjusted motion-amplitude declined. These data represent a replication of capture of visual direction with a continuous line (for reasons explained in the Section 1). However, if the monocular line was flashed for 67 ms at the moments of minimal and maximal disparity of the fusion stimulus, the adjusted motion-amplitude was significantly smaller than with a continuous line in Experiment 1 ($F[1,5] = 60.9$, $P = 0.0006$ for the white line, $F[1,5] = 21.7$, $P = 0.0056$ for the green line, $F[1,5] = 37.8$, $P = 0.0017$ combined for both lines) and in Experiment 2 ($F[1,16] = 9.63$, $P = 0.0068$). Thus, capture of visual direction was reduced with a flashed monocular line.

Fig. 4 gives an overview of all 17 individual data of Experiment 2: a scatter plot of the adjusted motion-amplitude of the monocular line versus the gain of the vergence eye movements is given in each experimental condition. In the condition of a continuous line and a small gap width of 16 min arc, we expect capture of visual direction, i.e., adjusted motion-amplitudes of close to 39.5 min arc. As shown in Fig. 4A, this was the case in part of the sample, but not in all individuals: some subjects adjusted much smaller motion-amplitudes, partly as small as 25 min arc. It could be that capture did not occur in these subjects. However, we rather believe that they were not able to reliably perform the adjustment, since the present sample of subjects was not experienced in this task, e.g., one subject made six repeated adjustments of the motion-amplitude in the range of 6–39.5 min arc (mean 25 min arc) with a continuous line and the smallest gap. Irrespective of the reasons of these unexpected small amplitudes, a comparison of the correlations in conditions of capture (continuous) versus reduced capture (flashed) can only be made in a sample of subjects who showed the capture effect with a continuous monocular line; this is the initial baseline condition. Therefore, we confined the further analyses on those 10 subjects who adjusted—with a continuous line at the 16 min arc gap—a motion-amplitude larger than 35 min arc. This was the range found in Experiment 1 with experienced observers, assuming that such motion-amplitudes reflect capture of visual direction. Fig. 3C gives the motion-amplitude of the monocular line in the subgroup of these 10 subjects; the pattern of result was very similar as for the six subjects in Experiment 1. For these 10 subjects (indicated by closed symbols), Fig. 4 shows the correlation coefficients between the adjusted motion-amplitude of the monocular line and the vergence gain.

We expect that these subjective and objective measures of vergence should not be correlated if capture of visual direction occurs since—in this case—the adjusted motion-amplitude of the monocular line is independent on the vergence eye movements performed. Accordingly, with a continuous line at the smallest gap width of 16 min arc, a negligible correlation of $r = 0.18$ was found (see Fig. 4A). As the gap increased up to 144 min arc with a continuous line, the effect of capture of visual direction should decline: as expected, the number of subjects with motion-amplitudes larger than 35 min arc declined to 3 and the correlation coefficient increased up to 0.47 (Figs. 4A–D).

If capture of visual direction is reduced with the flashed monocular line, the adjusted motion-amplitude may more likely be a subjective measure of the vergence gain, i.e., of the left eye vergence component, since the line was presented to the left eye. This was confirmed since with a flashed monocular line, we observed a more positive correlation than with the continuous line at each gap width. At the smaller gap widths of 16 and 48 min arc, the correla-

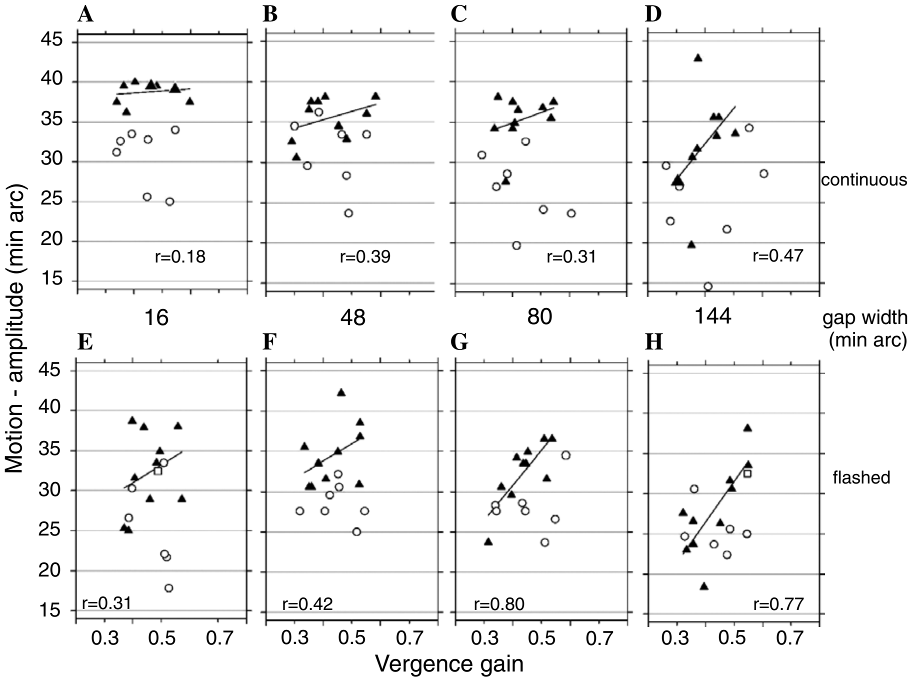

Fig. 4. Scatter plots of the adjusted motion-amplitude of the monocular line versus the vergence gain of the fundamental frequency, separately for the continuous and flashed line at the gap width of 16, 44, 80, and 144 min arc, respectively. Data points of 17 subjects in Experiment 2 are shown. The filled triangles, regression lines, and correlation coefficients—however–refer to the sub-sample of 10 subjects, who showed motion-amplitudes larger than 35 min arc with a continuous monocular line at the gap width of 16 min arc (A). Correlation coefficients are significant ($P < 0.05$, one-tailed) if larger than 0.75 (including a Bonferroni correction). In some cases, two symbols occupied the same spot: larger triangles indicate two overlapping triangles and open squares indicates an open circle that was shifted downwards by one symbol size in order not to overlap a triangle.

tions of 0.31 and 0.42 remained insignificant (Figs. 4E and F). But at the larger gap widths of 80 and 144 min arc (Figs. 4G and H), the correlations reached the amount of 0.80 and 0.77, respectively, and were significant ($P < 0.05$, one-tailed, including a Bonferroni correction according to the eight correlations tested). In these conditions, only 1 or 2 subjects adjusted motion-amplitudes larger than 35 min arc and these might not indicate capture since they corresponded to the largest gain values.

Fig. 5 shows the mean of all eye movement components of the sub-sample of 10 subjects. In response to the symmetrical fusion stimulus, we found a vergence amplitude that decreased from 29 to 26 min arc as the gap width increased, presumably since the fusion contour became less

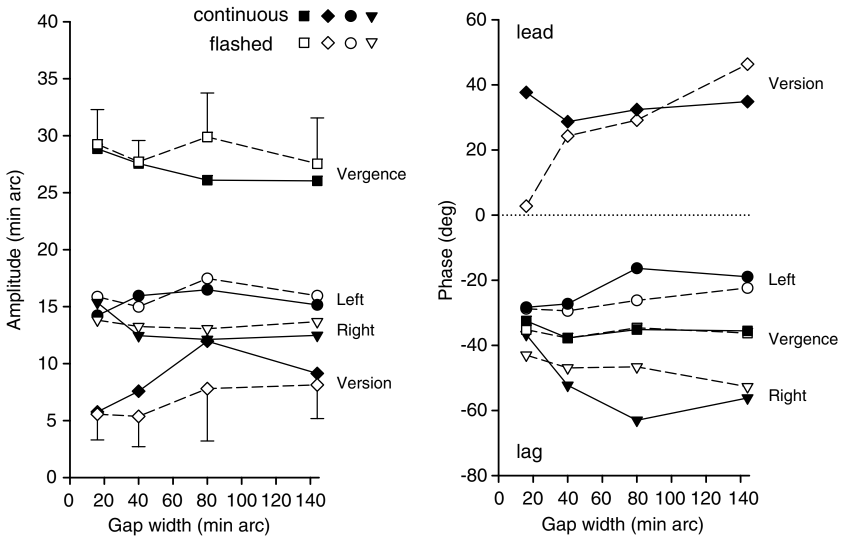

Fig. 5. Mean and typical standard deviations of the movement amplitude (min arc) and phase (deg) of the left eye and right eye and of the vergence and version components. Data refer to the sub-sample of 10 subjects, having shown capture of visual direction with a continuous monocular line (see Figs. 3 and 4). The vergence stimulus had an amplitude of 80 min arc in the triangular-wave and 65 min arc in the fundamental frequency. Positive and negative figures of the phase values indicate a phase lead and phase lag, respectively.

effective at more peripheral positions. The vergence phase delay was about −35 deg. The left eye had generally a larger movement amplitude and a smaller phase delay than the right eye (in all 10 subjects), which represents a version component. The phase values of the version component was always positive, which represents a phase lead. A phase asymmetry of 8.4 deg between the eyes was already present at the smallest gap width and increased with the gap width so that the version component increased from 6 to about 9 min arc for a continuous line. The flashed line resulted in a smaller version component and phase asymmetry between the eyes than the continuous line.

The version component could be a response to the motion of the monocular line. It must be considered, however, that the motion-amplitude was neither constant nor well defined, as it was permanently adjusted to subjective stationarity. Thus, the motion-amplitude varied across conditions, between individuals and over time during each trial. Therefore, a version gain factor (defined as response/stimulus) cannot be given. From the vergence amplitude of 26–29 min arc, we calculated a vergence gain of 0.40–0.46 (corresponding to the fundamental frequency of the triangular-wave).

4. Discussion

With a continuous monocular line, we replicated capture of visual direction in dynamic vergence (Erkelens & van Ee, 1997a, 1997b): when a periodic vergence stimulus was presented by a counter phase movement of half-images in the two eyes by an amplitude of 39.5 min arc, most subjects adjusted a motion-amplitude of a monocular line of nearly 39.5 min arc when the fusion contour was close to the monocular line. This cannot be explained by the vergence movements performed that showed large errors in these conditions; rather, the monocular line appears to receive the visual direction of the closely adjacent fusion contour.

A subjective motion-amplitude of 39.5 min arc (as expected from capture of visual direction at the smallest gap of 16 min arc) was not exactly adjusted by all six subjects in Experiment 1: they adjusted amplitudes in the range of 35–40 min arc. The smaller of these amplitudes might be a result of the fact that the viewing conditions might not have been optimal: the edges of the CRT screen and the rim of the shutter glasses might have been possible reference frames for the vergence stimulus. Some subjects did not see the dynamic fusion stimulus as completely stationary, but noticed residual horizontal motion. Nevertheless, with the continuous monocular line (presented to the left eye), adjusted motion-amplitudes of more than 35 min arc cannot be explained by the vergence eye movements since the left eye movement amplitude was about 15 ± 2 min arc (Fig. 5).

However, with a flashed monocular line, a clearly smaller motion-amplitude was found. At the smallest gap width of 16 min arc (where capture of visual direction was most effective with a continuous monocular line), the mean motion-amplitude declined from 38 min arc with a continuous line to 27 min arc with a flashed line (in Experiment 1). The latter figure is much smaller than the motion-amplitude of the random-dot pattern; thus, capture of visual direction was reduced by flashing the monocular line. As a possible explanation, one can assume that the 67 ms presentation time of the line was too short for the underlying mechanism to completely modify the visual direction of the line. However, the temporal properties of this mechanism are unknown at present.

If capture of visual direction occurs to a lesser extent with a flashed monocular line, the adjusted motion-amplitude was expected to be a subjective estimation of the performed vergence movement. Therefore, it was the aim of Experiment 2 to test a possible correlation between this subjective estimation with a flashed line and the objectively measured vergence gain. This correlation was insignificant at the smaller gap widths of 16 and 48 min arc, suggesting that the capture effect was still substantial in these conditions (at least in some of the subjects). However, significant correlations of about 0.8 were found at gap widths of 80 and 144 min arc. A gap width of 80 min arc means that the separation between the fusion contour and the monocular line (of 16 min arc width) is 32 min arc. This separation was sufficient to reduce capture of visual direction so that the motion-amplitude of a flashed monocular line was correlated with vergence gain, i.e., the adjusted motion-amplitude of the flashed monocular line reflected individual differences in vergence dynamics. However, the amount of variance explained was limited to 64%; the remaining proportion of variance will partly be due to measurement error and possibly residual capture of visual direction, since the adjusted motion-amplitude tended to be larger than the left eye movement amplitude.

This comparison of correlations between the conditions of capture versus reduced capture (i.e., continuous versus flashed monocular line) relies on the sub-group of 10 subjects who had confirmed the capture effect at the small gap width of 16 min arc (motion-amplitudes larger than 35 min arc in the continuous condition), which is the necessary initial requirement for this comparison. Fig. 3C shows that this sub-group of Experiment 2 ($n = 10$) and the sample in Experiment 1 ($n = 6$) show motion-amplitudes as a function of gap width that were very similar and both compare well with the mean result of the four subjects of Erkelens and van Ee (1997b), which is plotted as a dotted line in Fig. 3. This pattern of result seems to reflect the normal physiological behavior.

The random-dot pattern stimulated a predominantly vergence eye movement, superimposed by a smaller version component. A version component could occur, if one eye followed the dynamic vergence stimulus more accurately than the fellow eye; i.e., the left or the right eye would be the individual leading eye, irrespective of the actual stimulus conditions. However, the following observations suggest that the version component was mainly stimulated by the monocular line. Since the line was seen by the left eye, version induced by the line and vergence are in-phase in the left eye, but counter phase in the right eye; therefore, any version component induced by the line will shorten the left eye phase delay, but increase the right eye phase delay, as it was observed in all subjects. Such a phase difference and version was also found by Erkelens and van Ee (1997b) when a subject fixated the line; when fixating on the random-dot pattern, such a phase difference and version did not occur. One would expect that the continuous line is a better version target than the flashed line; accordingly, the phase difference between the eyes and the version component was larger with the continuous line. Thus, the version component is probably induced by the monocular line.

Since the version component was much smaller than the vergence component, the vergence response was rather symmetrical in the two eyes. This confirms that the complete vergence response of both eyes can be estimated by the left eye vergence component which is subjectively measured by the motion-amplitude of the line presented to the left eye.

The version component will not affect the adjusted motion-amplitude as a subjective measure of vergence (provided that capture of visual direction does not occur): this measure relies on the perceived displacement of the monocular line relative to the perceived position of the fusion stimulus, which is not altered if version movements should occur. Following Erkelens and van Ee (1997b), the head-centric direction of the symmetrical fusion stimulus remains unchanged despite vergence and version eye movements. Accordingly, in nonius tests of fixation disparity, e.g., the perceived position of nonius lines is not affected by version movements.

To summarize, we replicated the finding of Erkelens and van Ee (1997a, 1997b): the visual direction of a continuously presented monocular line was determined by the visual direction of a closely adjacent dynamic vergence fusion stimulus. However, this effect of capture of visual direction was reduced, if the monocular line was repeatedly flashed for 67 ms duration at intervals of 670 ms. When the spatial separation between the monocular line and the fusion contour was at least 32 min arc, the objectively measured vergence gain was correlated with the psychophysically adjusted motion-amplitude with a flashed monocular line, but not with a continuous monocular line. In conclusion, if one wishes to estimate the dynamic vergence response with psychophysical methods, effects of capture of visual direction can be reduced by using flashed nonius lines.

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