Motion Assimilation for Expansion/Contraction and Rotation and its Spatial Properties

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ABSTRACT

In a two-frame apparent motion display, a test grating was displaced horizontally or vertically in the presence of an inducer of which component gratings made up expanding/contracting or rotational motion as a whole. In the first experiment, we demonstrated that motion assimilation did occur for the test accompanied by the two-dimensional motion of the inducer. In the second experiment, we showed that spatial limit of motion assimilation for expansion/contraction or rotation was large, extending over at least a visual angle of 14 to 21 deg in diameter, but spatial summation did not occur within the limit. The results were discussed in terms of the interaction between local motion detectors and higher-order detectors which monitor global motion of the whole stimulus pattern.

INTRODUCTION

Motion assimilation refers to a visual phenomenon in which a physically non-moving (e.g. stationary or flickering) stimulus appears to move in the same direction as adjacent moving stimuli. Integrative process underlying motion assimilation, together with differential process underlying motion contrast, has been a matter of concern in an attempt to elucidate the interactions among local motion measurements (Braddick, 1993). For one-dimensional (translational) motion, substantial efforts have been made to examine the dependencies of motion assimilation on the stimulus parameters such as spatial frequency, size, luminance contrast, and eccentricity (Ramachandran & Inada, 1985; Ramachandran & Cavanagh, 1987; Nawrot & Sekuler, 1990; Murakami & Shimojo, 1993; Ohtani, Ido & Ejima, 1995; Ido, Ohtani & Ejima, 1997). A few small differences apart, most of these studies agree in that motion assimilation for one-dimensional motion may be ascribed to summation or facilitative interaction among local motion detectors tuned to the same direction of stimulus motion [Nawrot & Sekuler, 1990; Murakami & Shimojo, 1993; Ohtani *et al.*, 1995; Ido *et al.*, 1997: but see Ramachandran & Inada (1985) and Ramachandran & Cavanagh (1987) for a different interpretation].

For two-dimensional (expanding/contracting or rotational) motion, on the other hand, there have been few attempts to examine motion assimilation systematically. One relevant observation has been made recently by Morrone, Burr and Vaina (1995). In examining direction discrimination thresholds for a circular random-dot display which was composed of signal sectors containing coherently moving dots and non-signal sectors containing incoherent dots, they noted that 'the coherent motion did not seem to be confined to the signal sectors, but the whole display appeared to expand, rotate and slide' (p.507). Although their observation is interesting, as they noted, and suggestive of motion assimilation for two-dimensional motion, the experimental task in their study (direction discrimination of global dot motion) does not allow one to conclude that incoherent motion in the non-signal sectors was assimilated by coherent motion in the signal sectors.

Motions of objects in the external world and self-motion of an observer are represented by two-dimensional optical flow on the retina, and the optical flow, somewhat complex as it is, may be theoretically decomposed into a small number of elementary components including divergence and curl (Koenderink & van Doorn, 1975; Koenderink, 1986; Longuet-Higgins & Pradzny, 1980). There is a growing body of psychophysical and physiological support for the existence of mechanisms (or detectors) which detect expanding/contracting and rotational motion by combining local motion signals of different directions from different locations (Regan & Beverley, 1978, 1980, 1985; Freeman & Harris, 1992; Morrone *et al.*, 1995; Wright & Gurney, 1995; Gurney & Wright, 1996; Saito, Yukie, Tanaka, Hikosaka, Fukada & Iwai, 1986; Tanaka, Fukada & Saito, 1989; Tanaka & Saito, 1989; Duffy & Wurtz, 1991 a, b; Orban, Lange, Verri, Raiguel, Xiao, Maes & Torre, 1992; Graziano, Andersen, & Snowden, 1994). Given the theoretical and experimental evidence, it is intriguing to examine whether motion assimilation occurs not only for one-dimensional motion but also for two-dimensional motion, and if it does, it is informative to quantitatively examine the stimulus dependencies of motion assimilation in elucidating the process underlying the generation of two-dimensional motion signals.

In the present study, we first demonstrate that motion assimilation occurs for a test grating (presented in a two-frame motion display) accompanied by an inducer of which component gratings make up expanding/contracting or rotational motion as a whole. We then examine the spatial limit and the spatial summation characteristic of two-dimensional motion assimilation.

EXPERIMENT 1

Methods

Observers. Two of the authors (YO, MT) and an undergraduate student (TN) served as observers. TN was naive to the purpose of the present study. All were emmetropic.

Insert Figure 1 around here

Apparatus and stimuli. A TOTOKU CV172 color CRT monitor with 100 Hz refresh rate was driven by a VSG 2/3 stimulus generator (Cambridge Research Systems) with a pseudo 12-bit luminance resolution for each of the R, G, and B channels. The gamma nonlinearity of the monitor was corrected using a look-up table. The stimulus configuration is shown in Fig.1. The stimulus consisted of 4 black/white patterns each of which was presented within a circular window subtending 3 deg in diameter. The 4 patterns were located at 3.5 deg from the center of the display. The component patterns were one-dimensional (horizontal or vertical) sinusoidal gratings of which spatial frequency was 1.3 cpd. The luminance contrast of the gratings (the Michelson contrast) was 0.2. The mean luminance of the display was 29 cd/m^2 . One of the 4 component patterns was used as a test stimulus (termed as 'test') and the other three were used as inducing stimuli ('inducer'). A fixation point (a black dot of 0.05 deg) was presented continuously at the center of the display.

The motion sequence in a trial consisted of two frames, each of which was presented for 250 msec. Between the two frames, the gratings, but not the stimulus windows, were displaced abruptly with an inter-stimulus-interval of 0 msec (but actually restricted by the refresh rate of the monitor). The direction and magnitude of displacement were defined as the phase difference between the gratings in the first and the second frames, with rightward (for horizontal motion) or downward (for vertical motion) displacement expressed as a positive value. The phase difference of the test was varied from 90 to 270 degrees; at 180 degrees, the test was a two-frame counterphase grating. In this paper, the term 'degree' is used to denote the phase angle, while 'deg' is used to denote the distance in visual angle (and the angle of rotation; see below). The phase difference of the inducer was either 90 or 270 degrees. The inducing grating with a phase difference of 90 degrees appeared to move unambiguously to the right or downward, while the inducing grating with a phase difference of 270 degrees did to the left or upward. The orientations of the individual gratings (horizontal or vertical) were always orthogonal to the direction of the displacement (vertical or horizontal).

Figure 2 exemplifies the motion types of the inducer used in Expt. 1. The figure describes only the case in which the test is located at the right, but in the experiment all the four positions were employed for the test.

Insert Figure 2 around here

Expansion/Contraction [Fig.2(a)]: The motion directions of the inducing gratings were arranged so that they made up expanding or contracting motion as a whole. For expansion, the gratings at the top, the bottom and the left were displaced upward, downward and to the left, respectively. For contraction, the motion directions of the inducing gratings were reversed. The test was displaced horizontally.

Rotation [Fig.2(b)]: The motion directions of the inducing gratings were arranged so that they made up clockwise or counter-clockwise rotational motion. For clockwise (CW) rotation, the gratings at the top, the bottom and the left were displaced to the right, to the left and upward, respectively. For counter-clockwise (CCW) rotation, the motion directions of the inducing gratings were reversed. The test was displaced vertically.

Procedure. The observer sat in a darkened room and viewed the stimulus with his right eye at a distance of 88 cm from the display. Prior to each experimental block, the observer was informed of the inducer's motion type (expansion/contraction or rotation) and the test position which were to be employed in the block. In each trial, the observer was required to make a binary decision on the perceived direction of motion of the test ('left/right' or 'upward /downward') by pressing one of the two response keys. The phase difference of the test and the inducer's motion direction (e.g. expansion and contraction) were varied randomly across trials. Twenty trials were executed for each combination of the phase difference of the test and the inducer's motion direction. At least two blocks were carried out for each of the test position and the inducer's motion type. For one observer (YO), the data for the control condition in which only the test was presented were also collected for all the combinations of the position and the motion direction of the test.

Results

Motion assimilation for expansion/contraction and rotation. Figure 3 exemplifies one observer's (YO) data for the test with the two types of the inducer's motion and for the test without the inducer. The test was located at the bottom. For expansion/contraction [Fig.3(a)], the proportion of 'upward' responses is plotted as a function of the phase difference of the test. For rotation [Fig.3(b)], the proportion of 'left' responses is plotted as a function of the phase difference. The solid and dashed curves through the data points are the best-fitting functions obtained by using a logistic function

$$P=1/\{1+\exp[-\alpha*(\varphi-\beta)]\},$$

where P is the proportion of response, φ is the phase difference of the test, and α and β represent the slope and the uncertainty point (φ at which P=0.5) of the P vs phase-difference function. The values of α and β were estimated by the method of least squares.

Insert Figure 3 around here

For expansion/contraction, the fitted function for the test with the contracting inducer (open circles) is displaced to the left along the horizontal axis relative to the function for the control condition (filled triangles), while the function with the expanding inducer (filled circles) is displaced to the right. This indicates that, as compared with the control condition, the test with the contracting inducer is more likely to appear to move upward, and the test with the expanding inducer to move downward. Thus, the result shows the occurrence of motion assimilation in the direction of *expansion/contraction*. For rotation, the fitted function for the test with the CW inducer (open circles) and that for the test with the CCW inducer (filled circles) are displaced to the left and to the right, respectively, relative to the function for the control condition (filled triangles). This indicates that the test with the CW inducer is more likely to appear to move to the left, and the test with the CCW inducer to move to the right. This shows the occurrence of motion assimilation in the direction of *rotation*. The magnitude of motion assimilation was defined as the mean shift of the two uncertainty points for the tests with the inducer from the uncertainty point for the control condition, or equivalently, as half the difference between the uncertainty points for the tests with the inducer(1). In Fig.3, the magnitudes of motion assimilation are 14 degrees and 9 degrees for expansion/contraction and rotation, respectively.

Figure 4 shows the results for expansion/contraction and rotation for the three observers. In each panel, the magnitudes of motion assimilation for the different test positions are represented by the length of the lines with terminations. These values were estimated based on the data collected from the two experimental blocks (40 trials for each data point of the psychometric function), except for TN's results for rotation with the test located at the right and the bottom (see below). For expansion/contraction [Fig.4(a)], substantial motion assimilation is obtained for all the observers and for all the test positions. The averages of the magnitude of motion assimilation across the four test positions are 13 degrees (SD=2.4) for YO, 20 degrees (SD=6.9) for MT, and 10 degrees (SD=2.2) for TN.

Insert Figure 4 around here

For rotation [Fig.4(b)], clear motion assimilation is obtained for YO (average=12 degrees, SD=4.1) and MT (average=16 degrees, SD=7.0) for all the test positions, but the magnitude is relatively small for TN especially for the test located at the bottom. To test the significance of the results for this observer, additional 6 experimental blocks were run for each of the test at the right and at the bottom. For the test at the right, the average value of the magnitude of motion assimilation estimated for each of 8 blocks (20 trials for each data point of the psychometric function) was 6.3 degrees (SD=2.2); for the test at the bottom, it was 1.7 degrees (SD=1.9). The average values are shown in Fig.4(b). Ninety-five percent confidence limit of the average ranged from 4.4 to 8.3 degrees for the test at the right, and from 0.0 to 3.4 degrees for the test at the bottom. Thus, one may say that for this observer, significant magnitude of motion assimilation is obtained for the test at the right, and probably for those at the left and at the top. It is safer to reserve a definite conclusion concerning the test at the bottom.

Direction selectivity of motion assimilation for expansion/contraction and rotation. For the one-dimensional grating patches employed in the present study, only the direction of motion orthogonal to the orientation of the grating is recoverable due to the aperture problem (e.g. Adelson & Movshon, 1982). This raises a possibility that by using such stimuli, one might underestimate the magnitude of motion assimilation if the actual direction of assimilation does not lie along the axis of inducer's direction of motion. To examine the possibility, we measured the magnitude of motion assimilation as a function of the orientation of the test. In this experiment, the test was located at the right and the observer judged the direction of the test motion along the oblique axis (e.g. upward-right/downward-left).

Insert Figure 5 around here

The results for two observers (YO and TN) are shown in Fig.5. The abscissa represents the orientation difference (ÉΔ) between the test and the cardinal axis with counter-clockwise tilt expressed as a positive value; the cardinal axis is vertical for expansion/contraction and horizontal for rotation. The data for ÉΔ=0 deg are replotted from Fig. 4. It is clear that for both observers and for both types of inducer's motion, the magnitude of motion assimilation is the largest at ÉΔ=0 deg, and becomes reduced as the orientation difference is increased. The result indicates that the maximum motion assimilation indeed occurs along the direction axis of test motion commensurate with expansion/contraction and rotation.

Motion assimilation for one-dimensional motion. Auxiliary experiments were executed to confirm that motion assimilation for one-dimensional motion occurs with the present stimulus configuration and that no interaction occurs between orthogonal motions. For translation, both the test and the inducer were displaced either vertically or horizontally. For orthogonal motion, the test was displaced orthogonally relative to the inducer.

Insert Figure 6 around here

Part of the results for translation is shown in the two panels in Fig. 6. YO's data are for horizontal motion and TN's data are for vertical motion. Motion assimilation is obtained for all the test positions and for the two motion directions. The averages of the magnitude of motion assimilation across the four positions and the two motion directions are 15 degrees (SD=4.4) for YO and 6 degrees (SD=2.6) for TN. For orthogonal motion (data not shown), there is no indication of the effects of the inducer. The averages are 0.2 degrees (SD=1.5) for YO and 0.3 degrees (SD=1.3) for TN. The results for translation confirm the previous reports on motion assimilation for one-dimensional motion (e.g. Ohtani *et al.*, 1995). The results for orthogonal motion show that there exits no interaction between the test and the inducer which move orthogonally with each other.

EXPERIMENT 2

The results of Expt.1 suggest that some kind of motion detectors which monitor the two-dimensional global motion of the inducing gratings contribute to motion assimilation. Possible physiological correlates for such detectors may be motion sensitive neurons in the higher visual cortex, i.e. medial superior temporal (MST) area, of primates. It is well established that MST neurons respond selectively to expanding/contracting and rotational motion (Saito *et al.*, 1986; Tanaka & Saito, 1989; Tanaka *et al.*, 1989; Graziano *et al.*, 1994). An additional distinctive feature of MST neurons is that, as compared with motion sensitive neurons at the earlier cortical sites (i.e. V1 or MT), they have very large receptive fields (RFs) extending over several tens of deg in diameter (Saito *et al.*, 1986; Tanaka *et al.*, 1986; Tanaka & Saito, 1989; Duffy and Wurtz, 1991a). If motion assimilation obtained in Expt. 1 is actually mediated by such higher-order neurons (or detectors), it is expected that assimilation will occur over large spatial dimensions. To examine the expectation, we measure in Expt. 2 spatial limit of two-dimensional motion assimilation. Further, we examine whether or not spatial summation of assimilation occurs within the limit.

Methods

Observers. Two of the authors (YO and MT) took part in this experiment.

Insert Figure 7 around here

Stimuli and procedure. The stimulus configuration for the case of expansion is shown schematically in Fig. 7. The viewing distance was reduced by half (44 cm) to increase the size of the stimulus field (27 deg in diameter), but the size of the stimulus window was kept to be the same as that in Expt.1 (3 deg in diameter). The test designated by a shaded circle was located at 3.5 deg to the right of the center of the display. The motion direction of the test was either horizontal or vertical depending on the inducer's motion type.

For one type of the inducer, 8 or 17 (8 plus 9 more) inducing gratings were presented on the vertical meridian and in the opposite visual field to the test [Fig.7 (b) & (c)]. The gratings were located along (inner two or all the three) semi-circumferences of imaginary circles subtending 3.5, 7 and 10.5 deg in radius. We referred to this inducer as 'half-field-type'. For the other type of the inducer, the gratings were located along a single semi-circumference subtending either 7 deg or 10.5 deg [Fig.7 (d) & (e)]. We referred to this inducer as 'half-ring-type'. The motion direction of the inducing grating at each position was parallel (or perpendicular for rotation) to a radial reference line passing through the display center and the center of the inducing grating: as a whole, the gratings made up expanding/contracting (or rotational) motion. The orientation of each grating was orthogonal to its motion direction.

'Full-type' inducers, for which the inducing gratings are located at regular intervals along the whole circumference(s), were not used because change in the magnitude of motion assimilation with such inducers may well be contributed by local and probably one-dimensional motion interaction between the test and the inducing gratings close to the test. Consider the case for the full-type inducers moving in the direction of expansion [cf. Fig.7(b)-(e)]. The inducing gratings in the same visual field as the test, if added, would be oriented (nearly) vertically and move (approximately) to the right. Since they are located close to the test and have one-dimensional component motion parallel to the test, it is very likely that the result will be contaminated by the local and one-dimensional motion interaction. It is emphasized that we can eliminate most (if not all) of the artifact(s) by using the half-type inducers for which the inducing gratings are confined to the opposite visual field to the test(2).

The spatial frequency of the inducing gratings was changed in inverse relation to eccentricity: 2.6 cpd at the eccentricity of 3.5 deg (including the test), 1.3 cpd at 7 deg, and 0.65 cpd at 10.5 deg. With this frequency-scaling, at least about 2 grating cycles could be presented within all the stimulus windows. The frequency-scaled inducer was used because they gave rise to more vivid sensation of two-dimensional motion and the larger magnitude of motion assimilation as compared to the constant-frequency inducer. The other stimulus parameters and procedures were the same as those in Expt.1.

Results

The two panels in Fig. 8 show the results for expansion/contraction and rotation. In each panel, the magnitude of motion assimilation for the test with the two types of inducer (i.e. half-field or half-ring) is plotted as a function of the eccentricity of the outermost inducing gratings used in each condition. The data points represent the average values of motion assimilation estimated for each of 5 to 8 experimental blocks, and the vertical bars denote 95 % confidence limits. To show the confidence limits clearly, several data points are slightly displaced horizontally.

Insert Figure 8 around here

To examine the spatial limit of motion assimilation, consider first the results for the test with the half-ring-type inducer (open symbols). For expansion/contraction, the magnitude of motion assimilation for both observers decreases as the eccentricity of the inducer is increased from 3.5 deg to 7 deg, and the magnitude levels off at the largest eccentricity of 10.5 deg. For rotation, the magnitude for YO decreases with the increasing eccentricity, while the magnitude for MT remains approximately constant over the whole range of eccentricity employed. For expansion/contraction, significant motion assimilation is obtained for both observers up to the largest eccentricity of 10.5 deg. For rotation, motion assimilation occurs up to 7 deg for YO and 10.5 deg for MT.

For the test with the half-field-type inducer (filled symbols), the magnitude of motion assimilation for expansion/contraction remains almost constant as the number of the inducing gratings is increased, and the magnitude for rotation shows only a very slight tendency to increase. This means that the outer inducing gratings at the eccentricities of 7 and 10.5 deg are nearly ineffective for the enhancement of motion assimilation even though they are effective in producing assimilation when they are presented as the half-ring-type inducer.

DISCUSSION

Assimilation for two-dimensional motion

It seems unlikely that the results of Expt. 1 are explained solely in terms of interaction between one-dimensional motion signal for the test and individual one-dimensional signals for the inducing gratings. Notice that, for both expansion/contraction and rotation, the motion directions of the two inducing gratings adjacent to the test are orthogonal to the motion direction of the test (see Fig.2). Taking into account the results of the auxiliary experiment for orthogonal motion, it is implausible that each of the inducing gratings *per se* has any effect on the perceived direction of test motion. The other non-adjacent grating located at the opposite side relative to the test moves along an axis parallel to that of the test, but additional observation revealed that the inducing grating by itself also had no effects (neither motion assimilation nor other effects) on the perceived direction of test motion. Further, it was shown that the maximum motion assimilation occurred along the direction axis of test motion commensurate with expansion/contraction and rotation (see Fig. 5). Thus, one may conclude that the results of Expt.1 demonstrate the assimilatory effect of the *two-dimensional* motion signal for the inducer on the one-dimensional signal for the test, the former of which is generated by combining the individual local signals.

One possible model which may account for the present results is schematically shown in Fig. 9. The figure is for the case of expansion. At the first stage, one-dimensional motion signals for the component patterns are generated by the local motion detectors, each of which is tuned to a single direction of stimulus motion. At the second stage, the outputs of the local detectors tuned to different directions and located at different locations are combined to generate two-dimensional motion signal for the stimulus pattern as a whole. In the model, the higher-order detector is labelled as a 'global motion detector' so that the model may be applicable to translational motion as well. Sekuler (1992) has proposed a similar model for the global motion detector tuned to expansion which pools the outputs of the local detectors.

It is assumed that there exits an assimilatory influence from the higher-order detector's output on the local signals from the lower-order detectors: the output of each local detector is biased (represented by 'Σ' in the figure) so as to accord with the one-dimensional component signal at that location which is prescribed by the higher-order detector. Finally, the biased signals are fed into the decision process which yields a binary decision on the perceived direction of motion at each location in the stimulus pattern.

Insert Figure 9 around here

Consider the case in which, as shown in Fig. 9, the test is displaced by a phase angle of 180 degrees while the inducing gratings are displaced (by 90 or 270 degrees) so as to make up expanding motion. At the first stage, the local motion signal for the test is weak and ambiguous, whereas those for the inducing gratings are strong and unambiguous. At the second stage, the outputs of the local detectors are combined resulting in that a two-dimensional 'expansion' detector (but not the other detectors) is activated. Due to the assimilatory influence from the higher-order detector, the outputs of the local detectors are biased so as to accord with the global signal which signifies that the whole pattern is expanding. This will give rise to a sensory decision that the test moves away from the fixation point, which is what we found in the present study. The model is intended only to argue that explanation of our results requires an involvement of some kind of two-dimensional motion detectors, so experimental examination and quantitative formulation of the details are left open to future research.

Motion assimilation and receptive field size of two-dimensional motion detectors

The results of Expt. 2 for the test with the half-ring-type inducer suggest that the RF size of the two-dimensional motion detectors is rather large. If one makes some simplifying assumptions that motion assimilation we obtained is mainly mediated by the detectors whose RFs are centered at the center of the display, and that the half-ring-type inducer stimulated one-half region of the detectors' RFs, the RF diameter may be twice that of the semi-circumference radius of the inducer. This leads to an estimate of the RF size extending over more than 14 deg or 21 deg in diameter (154 or 346 deg^2 in area). These values are much larger than those inferred from the previous psychophysical evidence on the spatial summation for detection and discrimination threshold for motion direction. Watamaniuk and Sekuler (1992) found that discrimination threshold for global motion direction of a random-dot pattern decreased with increasing the stimulus area up to 63 deg^2. Morrone *et al.* (1995) showed that, within a circular field of 10 deg in diameter, direction discrimination for global motion improved with the area of the signal sectors including the coherent dots. Their results suggest that the RF of the motion detectors contributing to the discrimination performance extends over an area of about 80 deg^2. To the authors' knowledge, the value reported by Morrone *et al.* (1995) is the largest among those reported so far, but it is about half the estimate obtained in our study.

Our estimate of the RF size of the two-dimensional motion detectors is consistent with the physiological data on primates' MST neurons which respond selectively to expanding/contracting and rotational motion (Saito *et al.*, 1986; Tanaka & Saito, 1989; Tanaka *et al.*, 1989; Graziano *et al.*, 1994). These neurons have very large RFs which, on average, fall approximately within the range from

40 to 60 deg in diameter (Saito *et al.*, 1986; Tanaka *et al.*, 1986; Tanaka & Saito, 1989; Duffy and Wurtz, 1991a). This value conforms with or at least does not contradict our estimate of the RF size of the two-dimensional motion detectors contributing motion assimilation (14 to 21 deg or more in diameter).

In spite that motion assimilation extends over a large region, the results for the test with the half-field-type inducer showed little hint of spatial summation, suggesting that the magnitude of assimilation is mainly governed by the innermost three inducing gratings. We can not offer at present a definite explanation for the results, but we might speculate that motion assimilation is contributed not only by the sensory process (such as shown in Fig. 9) but also by the attentional process, the latter of which may be responsible for the lack of spatial summation. Some researchers have suggested that motion assimilation (or ‘motion capture’) may be modulated, or even ‘caused’, by visual attention (Ramachandran, 1992, 1996; Culham & Cavanagh, 1994). In the present stimulus configuration, observers may choose to ignore the more eccentric inducing gratings in the half-field-type displays, but to attend to them in the half-ring-type displays. Exploring such possibilities will help to elucidate the roles of the front-end (sensory) and the top-down (attentional) processes in the mechanisms underlying motion assimilation.

FOOTNOTES

(1) The uncertainty points for some of the control conditions deviate significantly from 180 deg [see Fig.3(a)]. Such a bias is systematic and rather large for vertical motion on and below the horizontal meridian; the observers tend to see downward motion more frequently than upward motion, while there is no systematic bias for vertical motion above the horizontal meridian and for horizontal motion (Ohtani & Ejima, 1997). So it is not appropriate to employ the physically equi-distance point (i.e. 180 deg) as a standard value. The psychometric functions for the test with the different directions of the inducer's motion (e.g. CW and CCW) are not always displaced symmetrically from that for the control condition [see Fig.3(b)], but, unlike the bias mentioned above, the asymmetric effect shows no systematic tendency with respect to the stimulus conditions manipulated in the present experiments. Since the asymmetric effect, if any, is not a major matter of concern here, we use half the difference between the uncertainty points as a measure of the magnitude of motion assimilation with which we can dispense with the data for the (substantial number of) control conditions. Note also that, in calculating the difference between the uncertainty points, the minuend and the subtrahend were interchanged with each other (depending on the test position and the motion type of the inducer) so as to make motion assimilation to be represented by a positive value. For example, for the test located at the right, the uncertainty point with the contracting (or CCW) inducer was subtracted from that with the expanding (or CW) inducer, whereas for the test located at the left, the latter was subtracted from the former.

(2) We came to think of using the half-type inducers, rather than the full-type ones, when we were coping with the comments on our earlier manuscript by one of the anonymous reviewers. We appreciate the insightful comments by the reviewer.

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LEGENDS

FIGURE 1: Schematic representation of stimulus configuration in Expt.1. The whole stimulus display subtended 13.5 deg in diameter. Four black/white sinusoidal gratings were presented within circular windows (3 deg in diameter) which were located at 3.5 deg from the center of the display. The spatial frequency of the gratings was 1.3 cpd. The luminance contrast of the gratings was 0.2. The mean luminance of the display was 29 cd/m^2 . The orientations of the gratings in the figure are for the case of expansion/contraction. Abbreviation. FP:fixation point.

FIGURE 2: The motion types of the inducer used in Expt. 1. The test is located at the right. The arrows in the top, the bottom and the left circles represent the motion directions of the inducing gratings: black arrows are for expansion and CW rotation, and gray arrows for contraction and CCW rotation.

FIGURE 3: The proportion of 'upward' [(a) expansion/contraction] or 'left' [(b) rotation] responses for the test located at the bottom as a function of the phase difference of the test. The data are for observer YO. For expansion/contraction, the open and filled circles represent, respectively, the data for the test with the contracting inducer and those with the expanding inducer. For rotation, the open and filled circles represent the data for the test with the CW inducer and those with the CCW inducer. The filled triangles show the data for the test without the inducer. Each data point is based on 40 trials. Solid and dashed curves represent the functions fitted by a logistic function described in the text.

FIGURE 4: Magnitude of motion assimilation for the three observers and for the four test positions. The upper three panels are for expansion/contraction and the

lower three for rotation. The scale (shown in the inset) for TN is different from those for the other two observers to facilitate display.

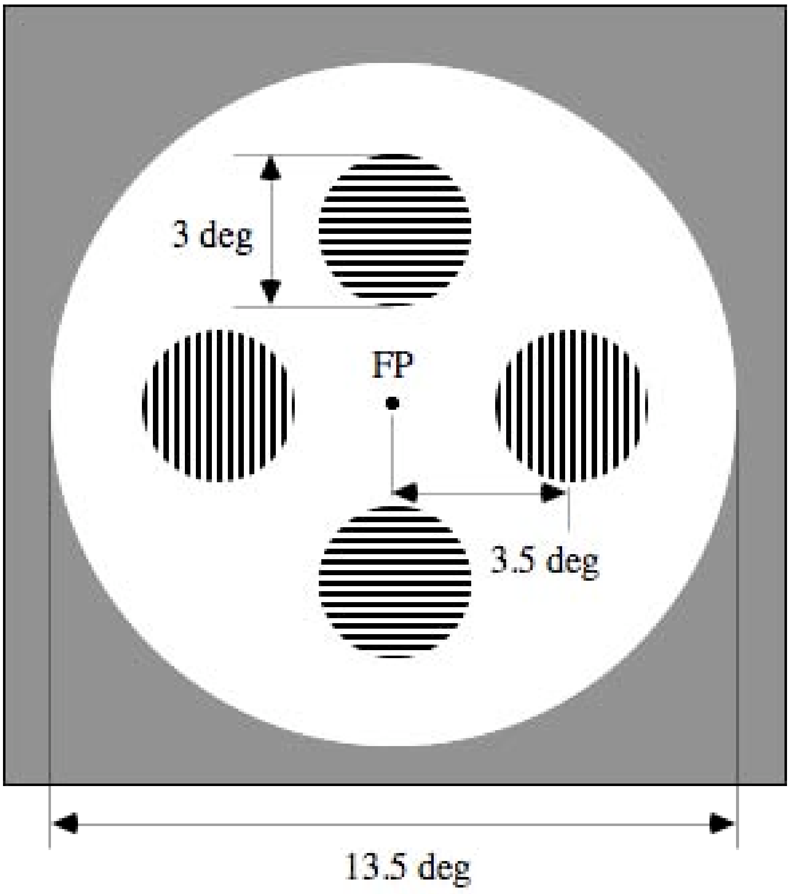
FIGURE 5: Magnitude of motion assimilation as a function of orientation difference of the test. Circles are for expansion/contraction and squares are for rotation. Abbreviations. e/c.: expansion/contraction. rot.:rotation.

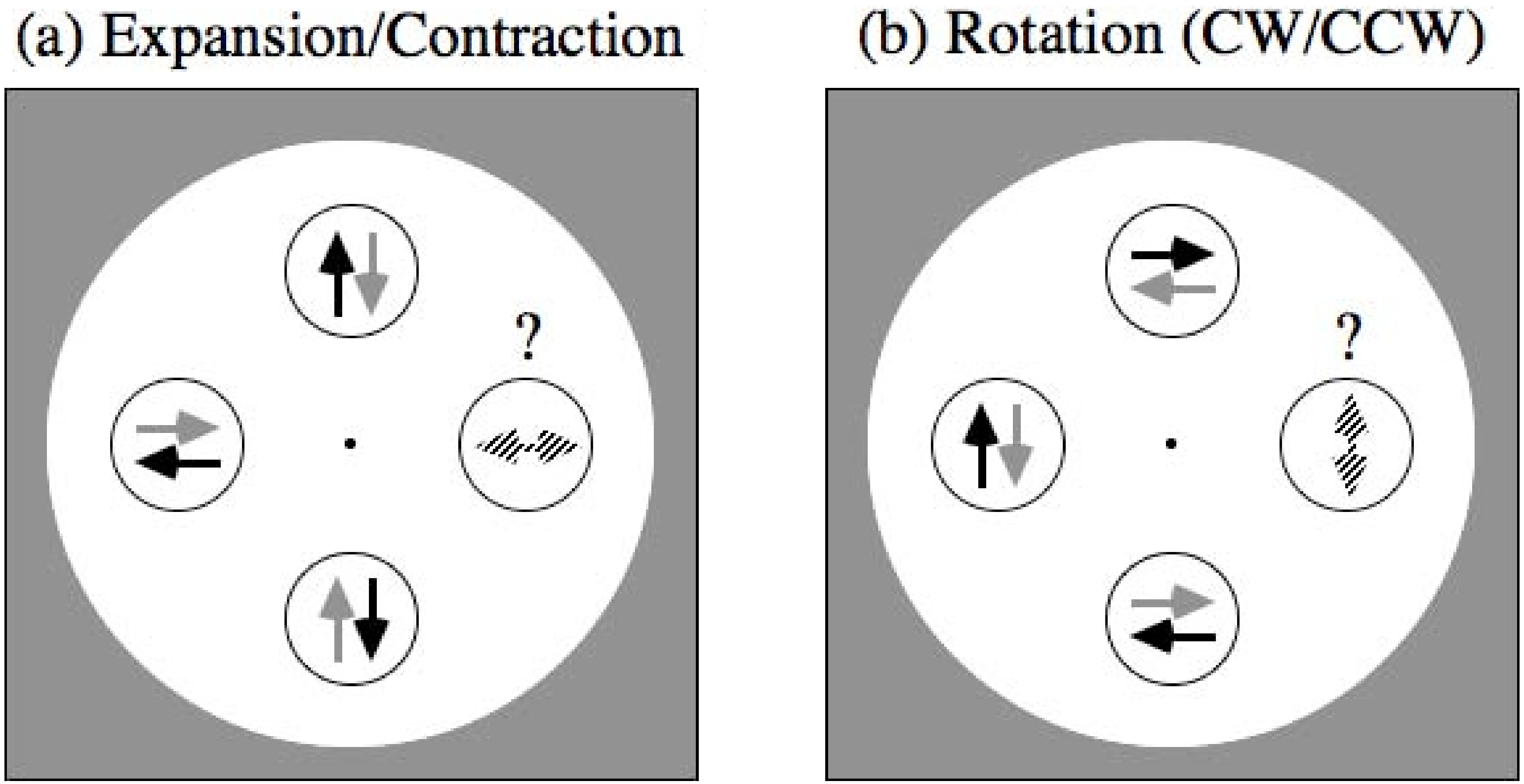
FIGURE 6: Magnitude of motion assimilation for translation. YO's data are for horizontal motion and TN's data are for vertical motion.

FIGURE 7: Schematic representation of stimulus configuration in Expt.2. Panels (b) and (c) are for the test (designated by a shaded circle) with the half-field-type inducer. Panels (d) and (e) are for the test with the half-ring-type inducer. Panel (a) depicts the stimulus configuration used in Expt. 1.

FIGURE 8: Magnitude of motion assimilation for the test with the half-field-type inducer (filled symbols) and for the test with the half-ring-type inducer (open symbols) as a function of the outermost inducing gratings used in each condition. Panel (a) is for expansion/contraction and panel (b) for rotation. The data points represent the average values estimated for each of 5 to 8 experimental blocks, and the vertical bars denote 95 % confidence limits. To show the confidence limits clearly, several data points are slightly displaced horizontally.

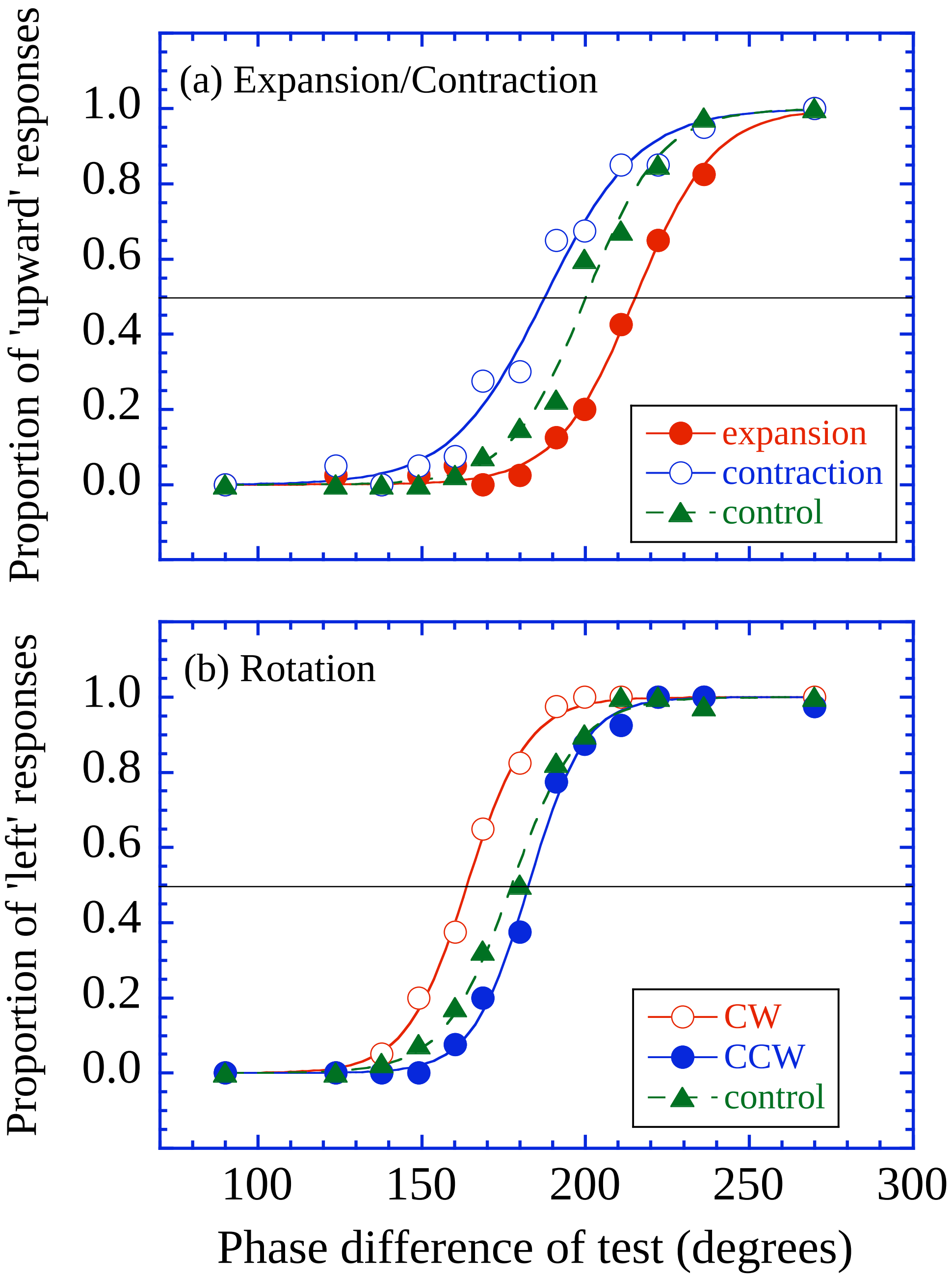
FIGURE 9: A schematic model which may explain motion assimilation for two-dimensional motion. The figure shows the case for the test with the inducer making up expanding motion. See text for details.


3 deg
FP
3.5 deg
13.5 deg

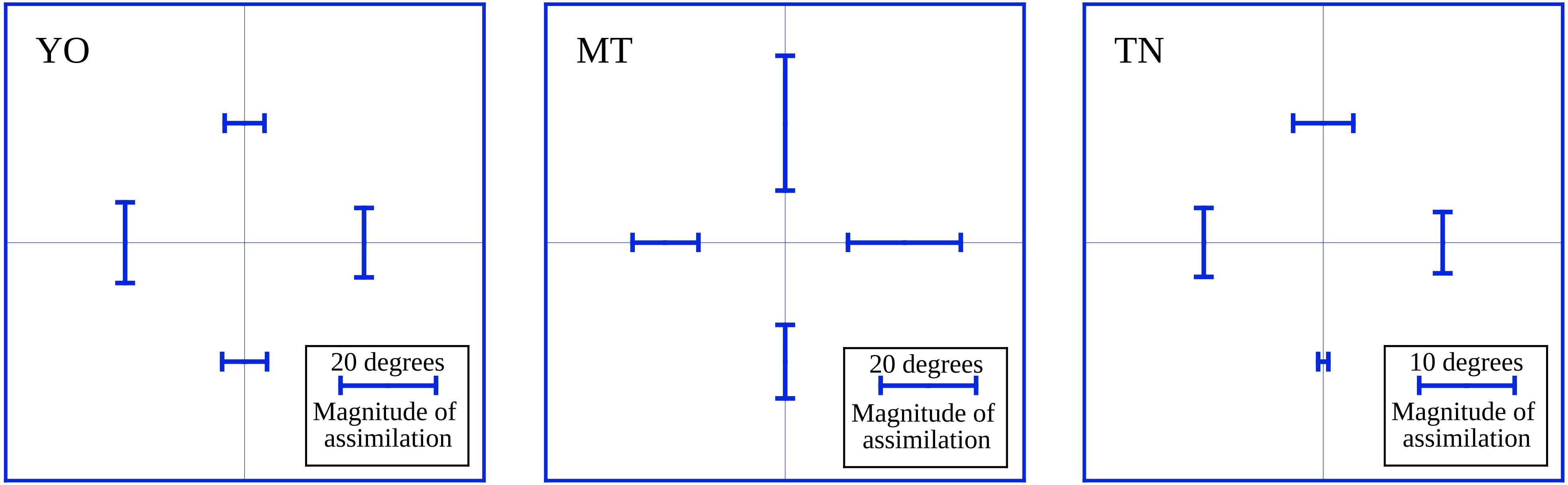


(a) Expansion/Contraction

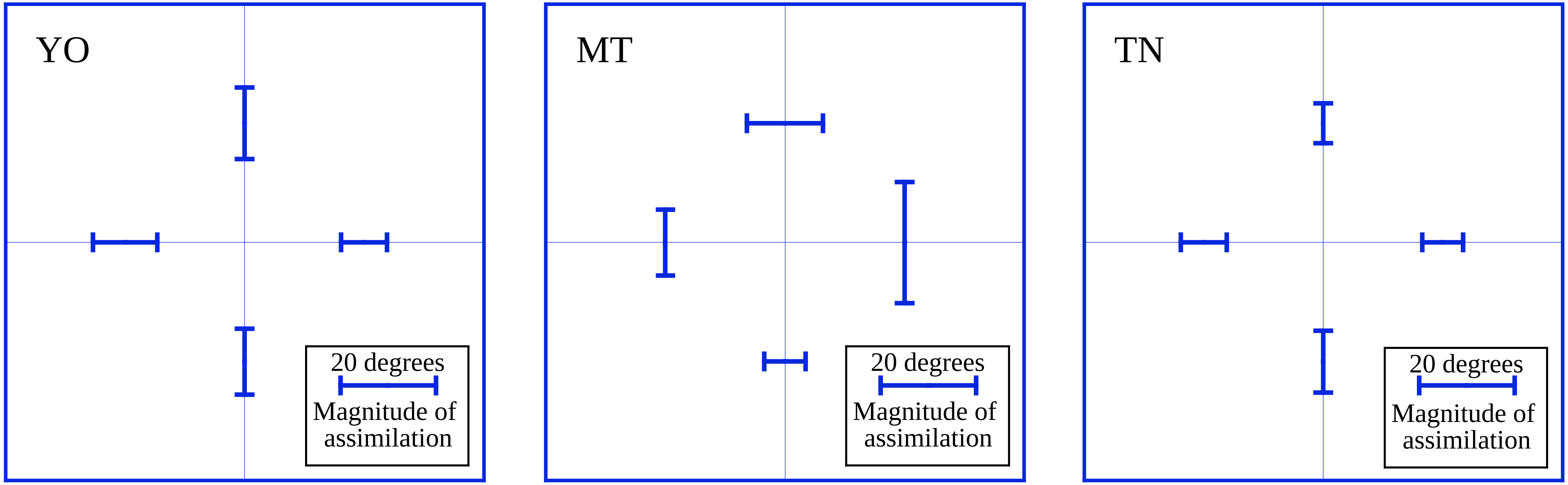
(b) Rotation (CW/CCW)

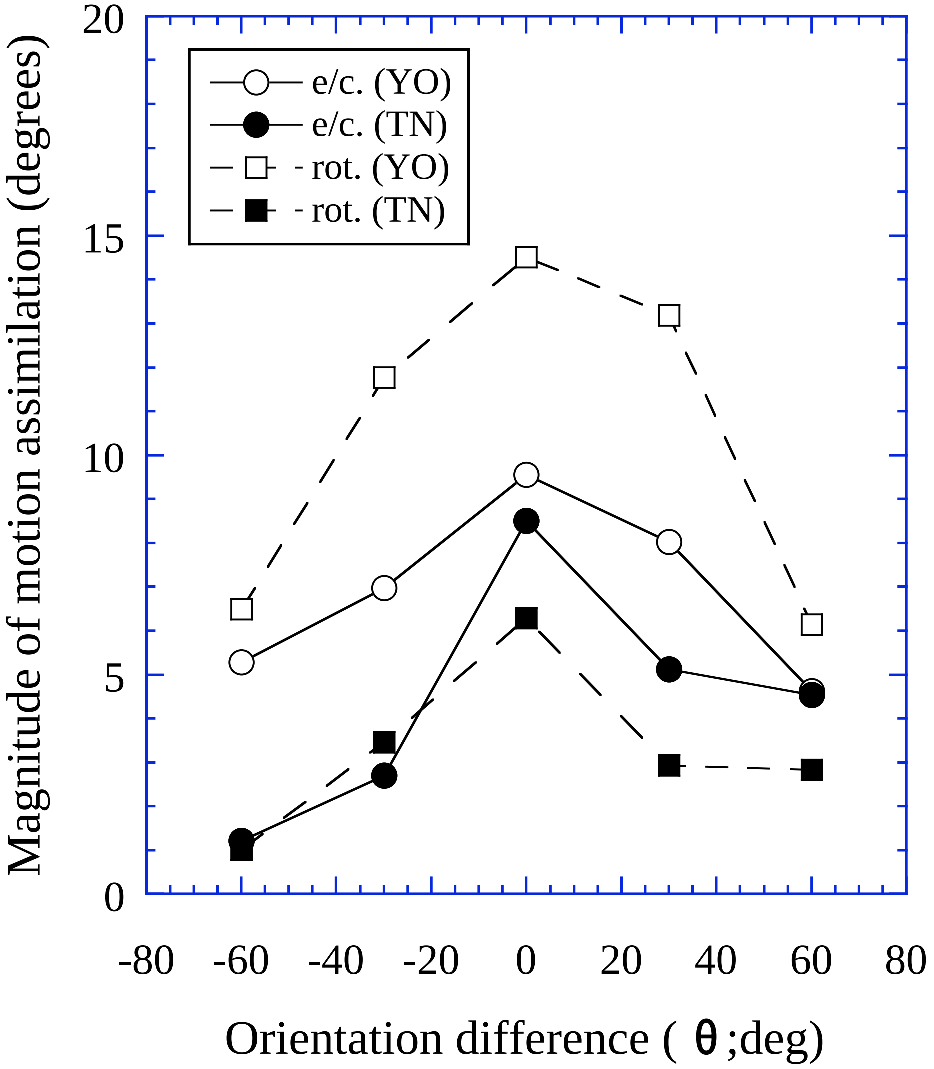

(a) Expansion/Contraction
Proportion of 'upward' responses
1.0
0.8
0.6
0.4
0.2
0.0
expansion
contraction
control
(b) Rotation
Proportion of 'left' responses
1.0
0.8
0.6
0.4
0.2
0.0
CW
CCW
control
100
150
200
250
300
Phase difference of test (degrees)

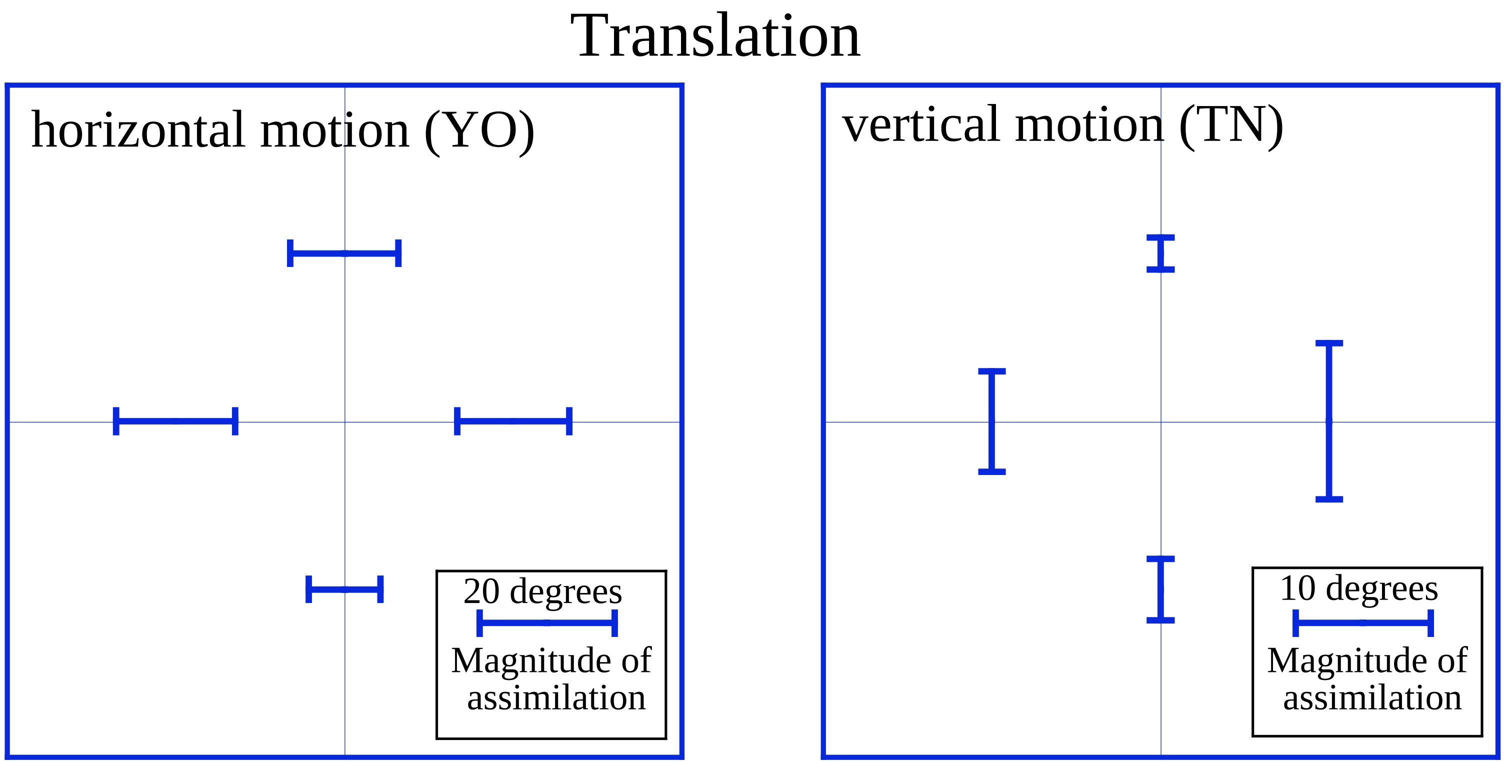
(a) Expansion/Contraction

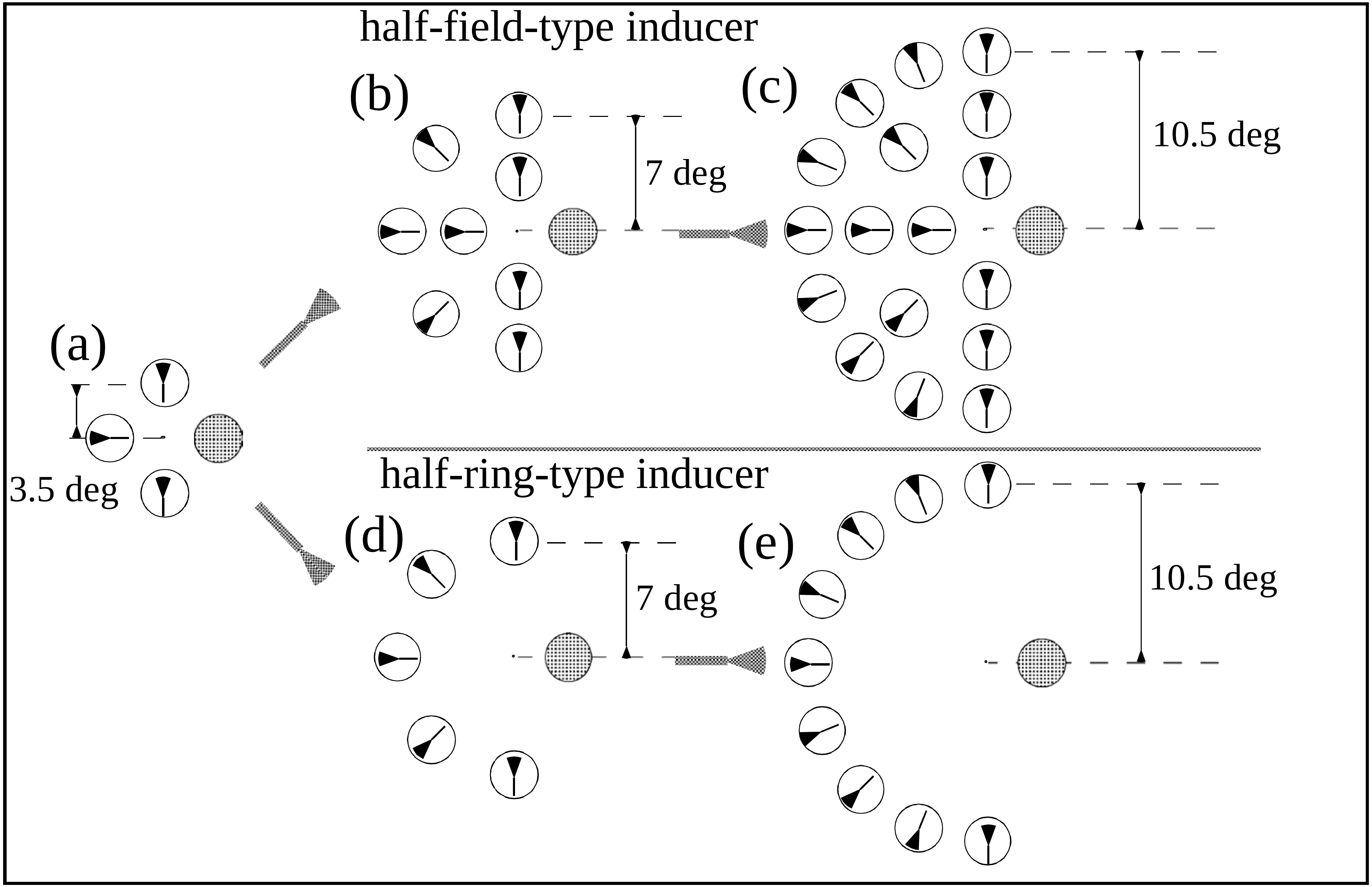


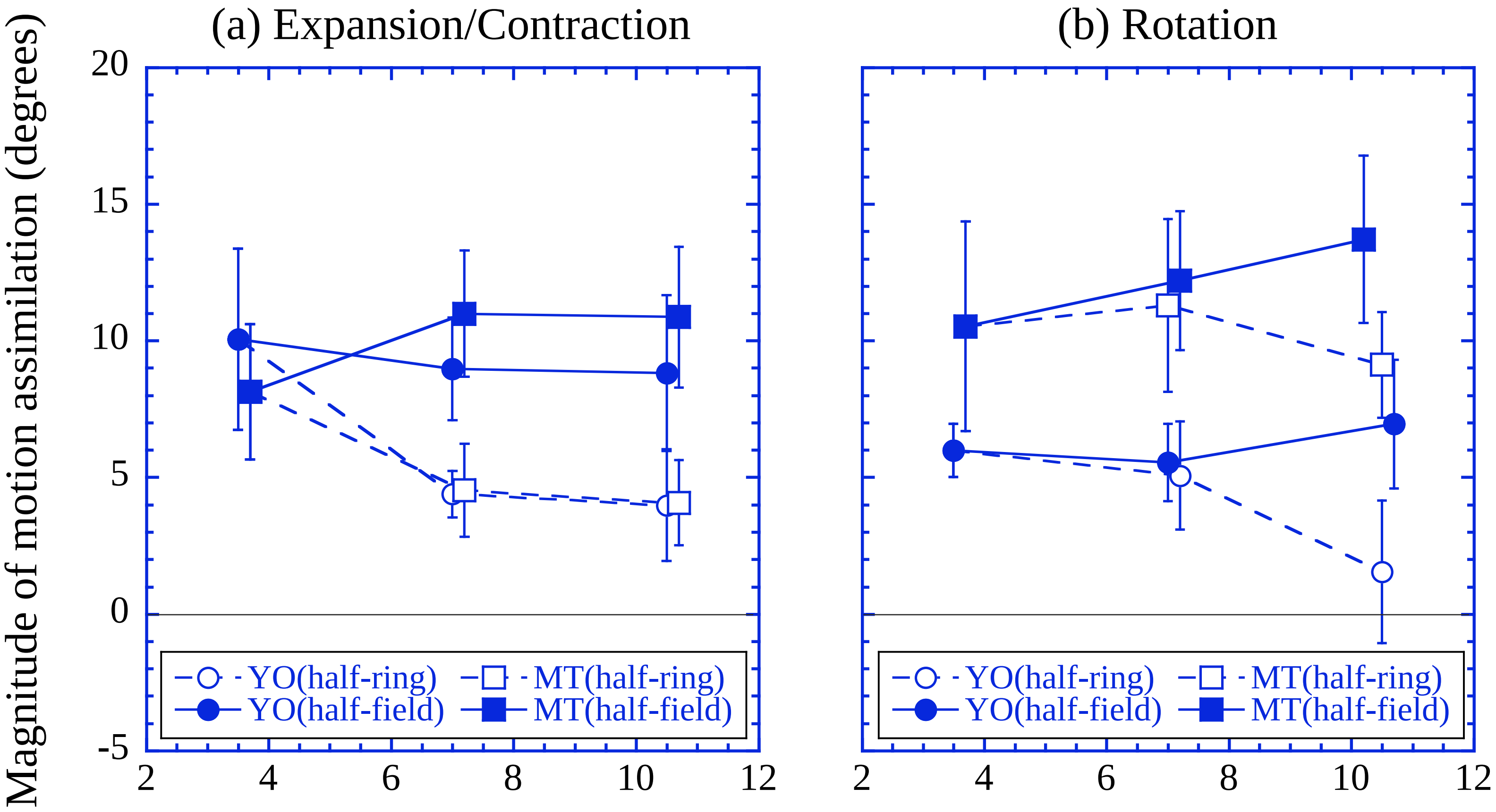
(b) Rotation

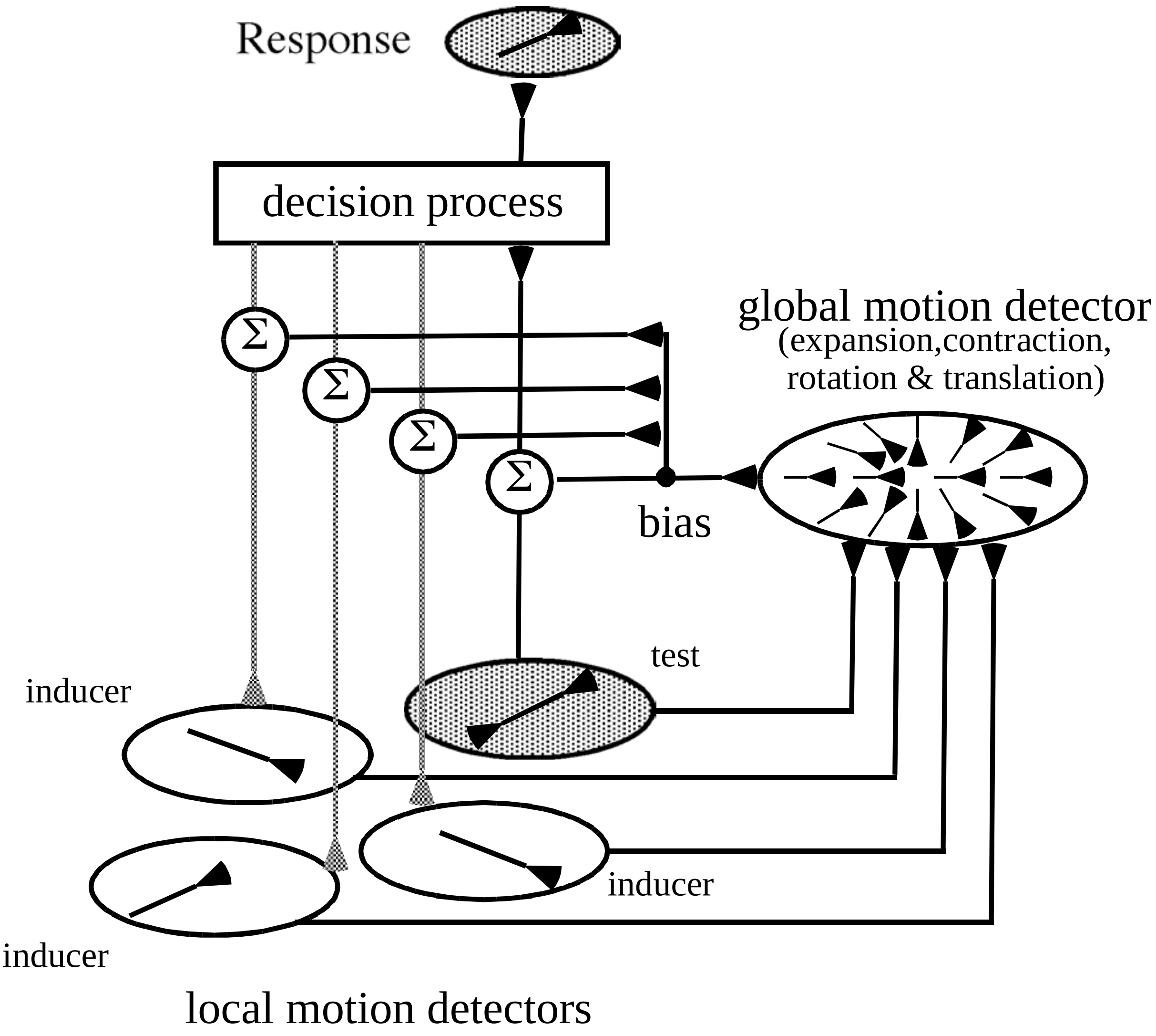



Magnitude of motion assimilation (degrees)
0
5
10
15
20
-80
-60
-40
-20
0
20
40
60
80
Orientation difference (θ ;deg)
e/c. (YO)
e/c. (TN)
rot. (YO)
rot. (TN)


Translation
horizontal motion (YO)
20 degrees
Magnitude of assimilation
vertical motion (TN)
10 degrees
Magnitude of assimilation


half-field-type inducer
(a)
3.5 deg
(b)
7 deg
(c)
10.5 deg
half-ring-type inducer
(d)
7 deg
(e)
10.5 deg


Magnitude of motion assimilation (degrees)
(a) Expansion/Contraction
(b) Rotation
20
15
10
5
0
-5
2
4
6
8
10
12
YO(half-ring)
MT(half-ring)
YO(half-field)
MT(half-field)


Response
decision process
global motion detector
(expansion,contraction,
rotation & translation)
Σ
Σ
Σ
Σ
bias
test
inducer
inducer
inducer
local motion detectors