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# Is Facilitation Responsible for the "Motion Induction" Effect?

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**When a horizontal bar is presented after a single dot is shown at one of its ends, an illusory motion is seen which has been dubbed "motion induction" in the literature. The phenomenon has been attributed to a facilitation process which asymmetrically modulates the inputs to motion detectors, for instance by some sort of changes in processing speed. Computer simulations of motion detector arrays show, however, that this basic effect has to be expected from the properties of simple motion detectors. It has been recently reported that the strength of the illusory motion increases with the subjective salience of the inducing element. New computer simulations demonstrate that this observation can be related to the control of the local gain of motion detector input signals by the feature contrast in a particular region of the stimulus. High-level attentional mechanisms or changes in transmission speed are not required to explain these phenomena. The implications of such local gain-control mechanisms for our understanding of second-order motion perception are discussed. © 1997 Elsevier Science Ltd.**

Motion Apparent motion Second-order motion Attention Model Feature contrast Gain control

## INTRODUCTION

When, in a two frame sequence, a small dot is replaced by a bar one of whose ends is located close to the previously presented dot, an illusory motion is perceived. The bar appears to grow, flowing from the end at the prior dot location to the end where no target was shown before. This effect, referred to as "motion induction", has been attributed to mechanisms which "speed up" the signals in regions of the visual field where the subjects pay attention, leading to a desynchronised excitation of a motion detector at the two bar ends (Hikosaka *et al.*, 1993b, 1991; von Grünau *et al.*, 1994, 1995, 1996). This explanation relates directly to our knowledge about the effects of attention, but a low-level explanation in terms of simple motion detecting mechanisms for this type of stimulation should be considered before invoking such high-level effects.

The crucial aspect of the stimulus, as far as the response of motion detectors is concerned, is that the centroid of the intensity distribution shifts between the two frames, from the centre of the dot to the centre of the bar. This shift should be reflected by the directional output of any reasonable motion detector, and has been found in a model of the correlation type (Zanker, 1994). Furthermore, there is independent psychophysical evidence that the shift in the centroid of a shape predicts the perceived motion direction (Allik, 1992; Morgan *et al.*, 1994). The actual motion detector model one has in mind is not critical; the shift of the intensity profile could be extracted by any luminance-based mechanism, and similarly the edges of the dot and bar could be matched by a feature-tracking mechanism (Ullman, 1981), leading to the same perceived illusion. Thus, the basic phenomenon of motion induction can be explained without the *necessity* to assume changes in temporal processing such as speeding up signals at certain locations. There are, however, experimental results which indicate more than the basic effect. In particular, when a horizontal bar appears within a regular array of oblique bars which are inducers, motion is observed within the bar away from the closest inducing element (von Grünau *et al.*, 1994). When a single inducing element (target) is oriented orthogonally to all other elements (distractors) in the array, and therefore "pops out" in a pre-attentive fashion (Treisman & Gormican, 1988; Wolfe, 1992), the motion illusion within the bar appears to be stronger. The effect of the target is best demonstrated by presenting the bar in the centre between a pop-out and a distractor element [cf. Figure 2(a)], eliciting a motion percept from the target inducer to the distractor inducer. This disambiguation of motion induction has been attributed to an attentional capture mechanism, and a speeding up was postulated for the region around the highly salient target (von Grünau *et al.*, 1996). These results go beyond the basic motion induction effect, because it has to be expected that the response of a simple motion detector is balanced in the

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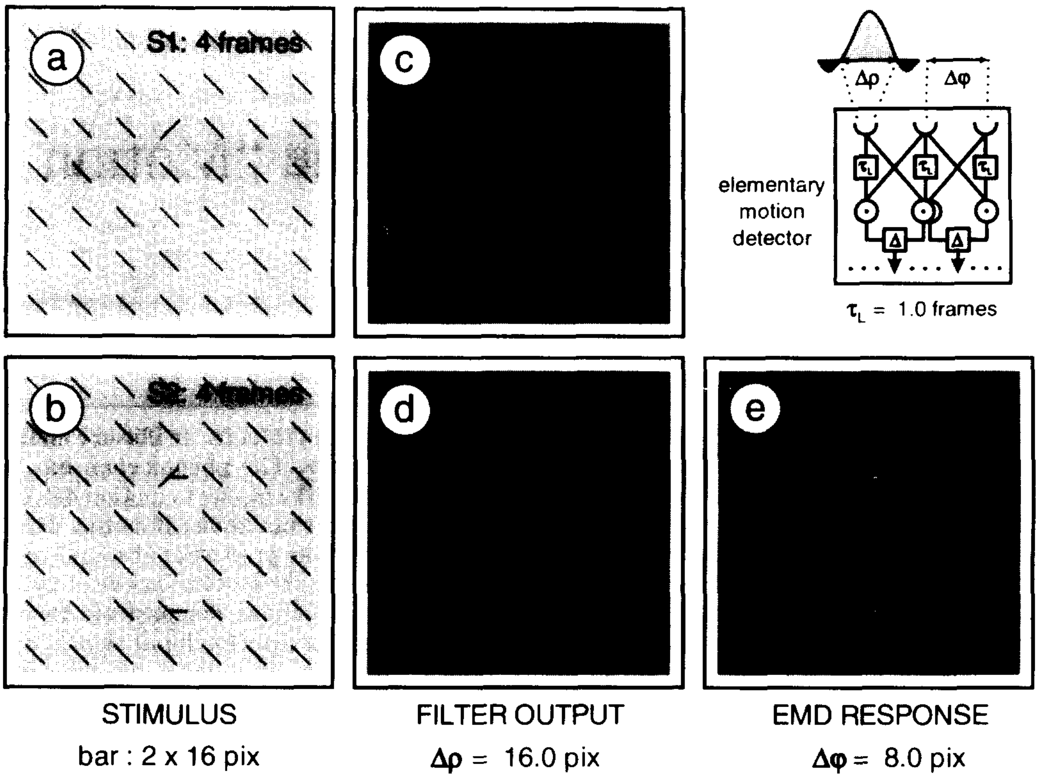


FIGURE 1. Two-dimensional representations ($256 \times 256$ pixel) of the stimulus, spatial filter output, and EMD response. (a, b) Direct intensity representation of the two stimulus frames. (c, d) In the output of the spatial filter the white and black areas indicate positive and negative signals, respectively, as compared to average grey corresponding to zero. (e) The grey-scale for the EMD response uses white and black regions to indicate locations where motion to the right and left is detected, respectively. The white rectangles mark the areas of interest displayed in Fig. 2, and were used to calculate the average 2DMD output for a given stimulus condition. The scheme at top right illustrates the main operations of the EMD model, together with the basic parameters, filter diameter ($\Delta\rho$), sampling distance ($\Delta\varphi$), and low-pass time constant ($\tau_L$).

stimulus in which the target and a distractor are mirror-symmetrical with respect to the centre of the bar.

Again, effects of attention on the temporal processing are not the simplest way to explain these experimental data. An alternative view will be illustrated by two sets of computer simulations. (i) The basic motion induction effect, to be expected for any adequate motion detector, is simulated with a two-dimensional array of motion detectors of the correlation type operating on spatially band-passed images. (ii) The influence of a pre-attentive pop-out target on the induced motion effect is simulated by a local change in gain, in which the strength of the motion detector input is modulated by some sort of feature contrast, which is here the difference in local orientation.

## THE 2DMD MODEL

Elementary motion detectors (EMDs) of the correlation type (for review, see Borst & Egelhaaf, 1989), have been chosen here for convenience as building blocks; others, such as the energy-model (Adelson & Bergen, 1985), give similar results or may even be formally equivalent. Spatial band-pass filtering was assumed in the two input lines of the EMD by filtering each stimulus frame with an isotropic two-dimensional DOG, with $\Delta\rho$ indicating the circular diameter of the excitatory centre. A first-order low-pass with time constant $\tau_L$ was used as temporal filter. The temporally filtered signal from one location was multiplied with the direct input from a second location, separated horizontally by the sampling interval $\Delta\varphi$, and the output of two such anti-symmetric subunits was subtracted (see model sketch in Fig. 1). These EMDs were arranged in a two-dimensional, "retinotopic", array covering a visual field of $256 \times 256$ elements, a network referred to as 2-Dimensional Motion Detector (2DMD). The two stimulus frames, the spatially filtered images, and the motion detector output, are shown in Figs 1 and 2; the spatial average of the 2DMD response is plotted as a function of the stimulus variables in Figs 3 and 4. Details of this model are described elsewhere (Zanker, in preparation).

So far, linear preprocessing by spatial band-pass filters was assumed for the input lines of the EMDs. Threshold and saturation nonlinearities of biological components, logarithmic compression, as well as nonlinearities related to more complex features of human motion perception (Derrington & Henning, 1993; Zanker, 1995) were ignored in this first, rather primitive modelling, to demonstrate that simple assumptions are sufficient to account for the basic motion induction effect. To examine the effects of pop-out targets, a specific preprocessing operator was included to extend the basic model by a local control of gain which is based on

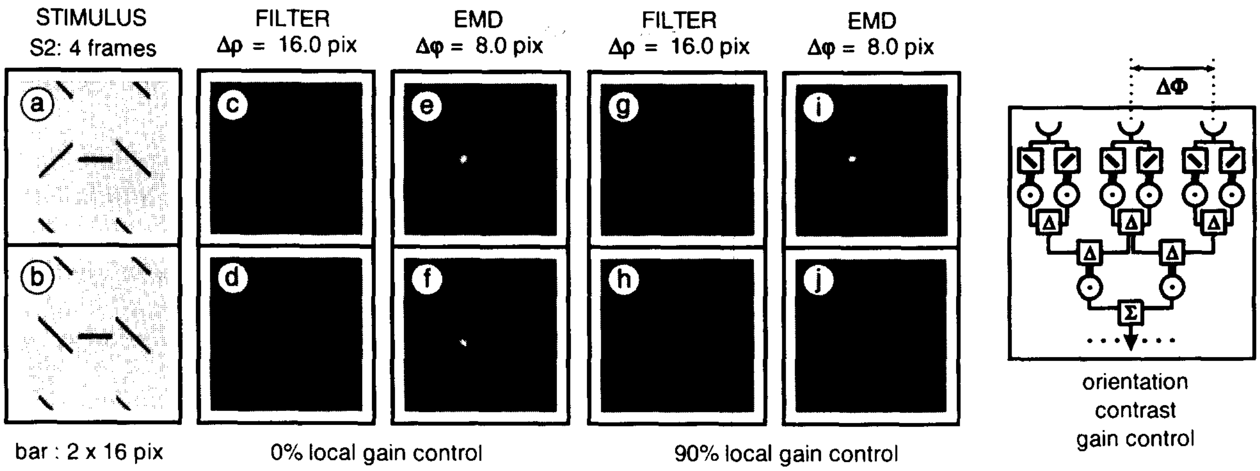


FIGURE 2. Two-dimensional representations of the area of 75 × 75 pixels around the horizontal bar. Stimulus (a, b), output of the preprocessing filter (c, d, g, h) and the EMD output array (e, f, i, j) for pure bandpass filtering (c, d, e, f) and local gain control (g, h, i, j) for frame 5 of the sequence; conventions as in Fig. 1. With local gain control, the target inducer disambiguates the balanced motion signal (cf. i with e) for a horizontal bar presented just between two inducing elements. The sketch illustrates the main operations of the local gain control mechanism; the average intensity within orthogonal slits (3 × 13 pixels, boxes with oblique bars) was computed; for each position the squared (circles, •) signals were subtracted from each other (boxes, Δ), and the difference of this local orientation across a fixed interaction distance (ΔΦ = 36 pixels) was summed for vertical and horizontal sample pairs (box, Σ), then low-passed with a triangular filter (20 pixels wide), and finally used to modulate the input of the EMD.

differences in orientation. This gain control is rather different from contrast normalisation used in some models of motion detection (Heeger, 1993) because it operates locally on the input of the directionally selective filters, is governed by features other than luminance contrast, and because it produces amplification instead of normalisation. Such modulation of the EMD input is not totally speculative. Orientation contrast, for example, has been postulated as one stimulus feature among others driving the pre-attentive pop-out and image segmentation in visual scenes (Nothdurft, 1991, 1993). Changes in the perceptual salience of objects or attributes can be interpreted in terms of changing local gain at various stages of visual processing, but in the context of directionally specific effects it may be sensible to modulate the gain of EMD inputs. This does not mean, however, that orientation selectivity necessarily precedes motion detection. Instead, it is proposed that a modulating input from some independent process drives the local gain by some sort of feedback.

Extraction of orientation contrast was incorporated into the computer simulations (see sketch in Fig. 2) by crude orientational filters. The stimulus intensity was averaged within orthogonal pairs of slits (vertical and horizontal, or diagonal pairs) for each array position, and the difference of the squared outputs was computed to represent local orientation independent of the stimulus sign (dark or bright). For each array position the differences of local orientation across the spatial interval ΔΦ (horizontal and vertical) were squared and averaged for both slit pairs, thus giving a measure of local orientation contrast irrespective of the actual orientation. The 2D-distribution of this signal was filtered by a spatial lowpass, with a space constant corresponding to approximately ΔΦ/2, and then used to modulate the band-pass filter output at every given location. The strength of such gain control could be varied between 0% when orientation contrast is ignored, and 100% in which case the amplitude of the EMD input is multiplied with orientation contrast. This control of the local gain by orientation contrast is a rather deliberate and crude operator which is tailored to the purpose of the present simulations. It is representative of a family of processes which change the gain of the local inputs according to the novelty or saliency of the stimulus at each location. Such an algorithmic interpretation of attentional mechanisms, which is considered for the detection of objects in search or segmentation paradigms (Nothdurft, 1993), adds an interesting feature to the basic motion detector response, as will be shown.

## THE QUALITATIVE 2DMD RESPONSE TO MOTION INDUCTION

The most basic simulation result is depicted in Fig. 1. The stimulus consisted of two images, S1 and S2 [Fig. 1(a, b)], each containing a matrix of 7 × 7 oblique bars (one oriented orthogonally to all the others). Two horizontal bars appear in S2, with their centres separated from those of their oblique neighbours by $\Delta x = 8$ pixels (half of the bar length). These images were filtered by two-dimensional DOGs with filter constant $\Delta\rho = 16$ pixels, which gives a centre frequency of about 0.04 cyc/pix, or 0.5 cyc/deg for a bar size of 16 pixels, corresponding to 1.5 deg. The band-passed images are shown as two-dimensional grey-scale images [Fig. 1(c, d)]. The response of the 2DMD network with an appropriate sampling interval is plotted [Fig. 1(e)] for one instant of time (frame 5). The white rectangular boxes in this frame indicate the region for which the average

2DMD response is calculated to give quantitative estimates of the simulation result for the two motion induction configurations. It can be seen immediately from the dominating white regions that the model, even in its simplest form, yields a positive response at the display of the horizontal bar, indicating rightward motion. The spatial distribution of the 2DMD exhibits local variations and even small regions of inversions shown as dark areas. This behaviour is a general feature of motion detectors, which is very well known for various types of stimuli (e.g. Egelhaaf *et al.*, 1989; Zanker, 1994) and underscores the necessity of some spatial or temporal averaging of the local detector outputs to compute direction selective response adequately. For the coarse spatial filtering shown here, the average response reaches 28% of the response of the same EMDs to an optimally tuned grating, and the positive sign corresponds exactly to the motion illusion from left to right.

When the two stimulus configurations are compared, with the horizontal bar appearing next to the target, and next to a distractor element [upper vs lower box in Fig. 1(e)], we see that the basic model would have difficulties distinguishing these two situations. To account for known perceptual differences, the extended model in which local gain is driven by orientation contrast was stimulated with the same stimulus sequence (data not shown), and yielded an average response 7 times as strong for the bar close to the target than for the bar close to a distractor element.

The strongest support for an effect beyond the basic EMD response has come from the condition in which the horizontal bar is presented just in the centre between two inducing elements. Psychophysical experiments with such stimuli demonstrated a strong bias to see motion away from the pop-out target (von Grünau *et al.*, 1996). The results of the corresponding simulations are depicted in Fig. 2, where two model versions are compared [cf. Figure 2(e, f) and Fig. 2(i, j)]. In the homogeneously filtered images [Fig. 2(c, d)] all stimulus elements are equivalent, but when local gain is controlled by orientation contrast [Fig. 2(g, h)] the target and the horizontal bar stand out from the surrounding elements. For both stimulus conditions, two regions of opposite sign appear in the response of the basic model near the two inducers, balancing each other [Fig. 2(e, f)]. The average 2DMD response is not strongly influenced by the type of inducing element, as shown by the average of 0.01% of the maximal grating response in both cases. When the EMD inputs are enhanced by local orientation contrast, the output signal is very small and balanced when the horizontal bar appears between two identical inducers, as shown by the average −0.07% grating response [Fig. 2(j)], but is comparatively strong and biased away from the target in the case of an inducing target element, with average 1% grating response [Fig. 2(i)]. The average response is small compared with the case with the bar in the vicinity of the inducing element (Fig. 1). This is mainly due to the fact that the displacement of the horizontal bar is sub-optimal, and the residual inverse response elicited by the distractor is not negligible. It should be noted that the average 2DMD output does not necessarily reflect the reliability of an observer in a direction-discrimination task (Zanker, in preparation).

## QUANTITATIVE 2DMD SIMULATION RESULTS

The computer simulations show that the basic motion induction effect can arise from the properties of simple motion detectors, and that the effect of pop-out inducers in a multi-object display can be predicted by a local gain control. To substantiate this explanation of the motion induction effect, it will now be shown that model simulations also yield quantitative results which closely match the experimental results.

In the first set of quantitative simulations, the centre of the horizontal bar was varied over a range from the centre of the left inducer ($\Delta x = 0$ pixel) to the centre of the right inducer ($\Delta x = 38$ pixels). To increase the spatial range of possible interactions of the individual EMD, the sampling distance $\Delta\varphi$ was 16 pixels in these simulations. All other parameters were maintained at the default values, and the strength of the local gain control was treated as a parameter. For all conditions the average response (Fig. 3) is zero when the bar is presented at the same position as the inducer. The response is positive or negative (i.e., motion to the right or left) when the bar appears in the right or left proximity of an inducing element, respectively, confirming the claim that the motion away from the target can be explained straightforwardly as a property of simple motion detectors. When the inducers are identical on either side [Fig. 3(a)], the zero-crossing occurs at $\Delta x = 19$ pixels, i.e., when the bar is presented exactly between the two inducers. In this location the induction effect indeed should be balanced, independent of the strength of local gain control [cf. Fig. 2(f, j)]. When a target inducer is presented on the left side and a distractor inducer on the right side, the curves are extended in the positive range [Fig. 3(b)], and in particular the zero-crossing is shifted to larger values of $\Delta x$, if the strength of the local gain control is increased. Thus, gain control shifts the 2DMD output towards motion away from the target inducer, even if the distractor inducer is closer, resembling the experimental observations of von Grünau *et al.* (1994, 1996). When comparing experiment and simulation, one has to keep in mind that the detailed shapes of the curves strongly depend on the actual model parameters. No attempt was made to fit the model output specifically to the experimental data, so avoiding specific assumptions about spatial configurations, combinations of detectors across different scales, the signal detection strategy, and output nonlinearities.

In a second set of quantitative simulations, the previous model was made more realistic by assuming that the local gain control does not operate instantaneously but needs some time to build up. A typical time constant $\tau_g$ of two means, for instance, that after two frames the gain control grows to about 75% of its steady state value. In this case, the effect of the target inducer should depend on the

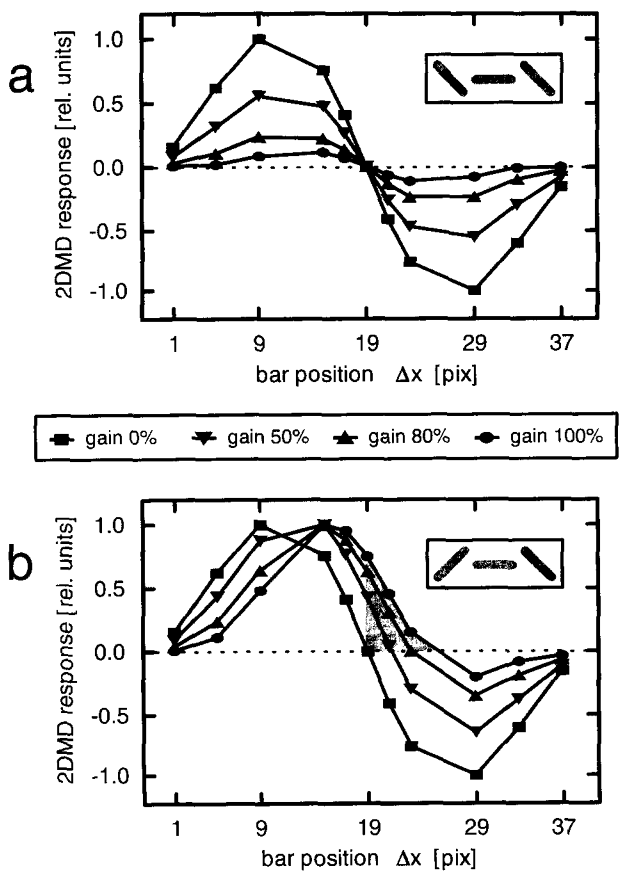


FIGURE 3. Average output of the 2DMD model with variable strength of local gain control, for variation of the horizontal position of the bar, $\Delta x$, between the left (0 pixels) and right (38 pixels) inducer. The results are normalised to the strongest response for the given set of model parameters. (a) If both inducing elements are distractors, the response is positive (motion to the right) when the bar is closer to the left inducer, and negative (motion to the left) when the bar is closer to the right inducer. The position of the zero-crossing is independent of the strength of the gain control. (b) If the left inducing element is a target, the range of positive response is extended and the zero-crossing is shifted to the right (shaded area) with increasing strength of local gain control.

duration of the first stimulus image, whereas the response elicited by a distractor should be achieved by the model at its full strength almost instantaneously. The results of such a simulation are presented as the maximum of the average response, occurring just after the transition from S1 to S2 (Fig. 4). When the bar is presented close to the inducer, the model response slowly increases with S1 duration in case of the target inducer [filled triangles in Fig. 4(a)], whereas the effect of the distractor element (open triangles) only exhibits a minor increase at small S1 duration, owing to the time constant of the motion detector itself. In this behaviour the model nicely corresponds to the psychophysical data (cf. Fig. 2 of von Grünau *et al.*, 1996). Simulations with the horizontal bar presented midway between two inducing elements used three different time constants for the gain control [Fig. 4(b)]. In this case, the gain control mechanism should fully determine the average 2DMD output, and indeed the rate with which the response builds up, depends on its time constant. With a $\tau_g = 1$, the final response strength is already reached at two frames S1 duration, whereas with $\tau_g = 4$ the final response strength is not reached during the maximum duration of six frames which were used in the present simulations. Thus, an immediate comparison of such simulation results with experimental data (e.g. Fig. 3 of von Grünau *et al.*, 1996) requires additional assumptions about the temporal properties of the model.

## CONCLUSIONS

The basic "pre-attentive" phenomenon of so-called motion induction has been modelled as a property of EMDs responding to shifts in the luminance distribution, and indications of higher processing, sometimes referred to as "facilitation by attentional capture", can be modelled qualitatively and quantitatively by changes in the local EMD input gain. Here, local gain was driven by the orientation contrast, as involved in texture segregation or the pre-attentive pop-out of image elements (Nothdurft, 1991). Other features, like colour, temporal characteristics, or texture, could be used correspondingly. Reports about multi-modal motion induction (von Grünau & Faubert, 1994) indicate that the local sensitivity to visual stimulation may even be modified by other modalities, such as acoustic signals. It can be argued that it is a semantic question whether the control of local gain by feature contrast, especially in a more general form, can be interpreted as the algorithmic formulation of attentional facilitation. Since all these effects can be easily linked to pre-attentive visual processing, the term "attention" may be reserved for the situation in which a balanced motion induction display is biased by means of voluntary attention (Hikosaka *et al.*, 1993a). In all these cases, however, there is no need to assume speeding up of motion detector signals (Hikosaka *et al.*, 1993b; von Grünau *et al.*, 1996), in terms of faster transmission speeds or changes in the detector time constant which are described in other contexts (Clifford & Langley, 1996). This view does not conflict with the observation that signals at higher intensities are generally detected faster (Hikosaka *et al.*, 1993b). For instance, after an increase of local gain the detection threshold could be reached faster by the stronger signal. Other cases of changes in speed of signal transmission (Stelmach *et al.*, 1994) may possibly be reduced to the same simple explanation.

A reason to reject low-level explanations of the motion induction effect (von Grünau *et al.*, 1996) was that observers report the sensation of a growing bar, whereas the model predicts a motion maximum near the border regions (cf. Fig. 2). The model clearly reqires further elaboration to relate the distribution of the motion signals to the object contours in two very general aspects. (i) Even a simple moving dot leads to an extended 2DMD response which is only loosely related to the dot's contour. (ii) The actual distribution of the motion signal depends on the spatiotemporal layout of the EMD, and a combination of sets of EMDs with different parameters may give a better estimate of position of the moving

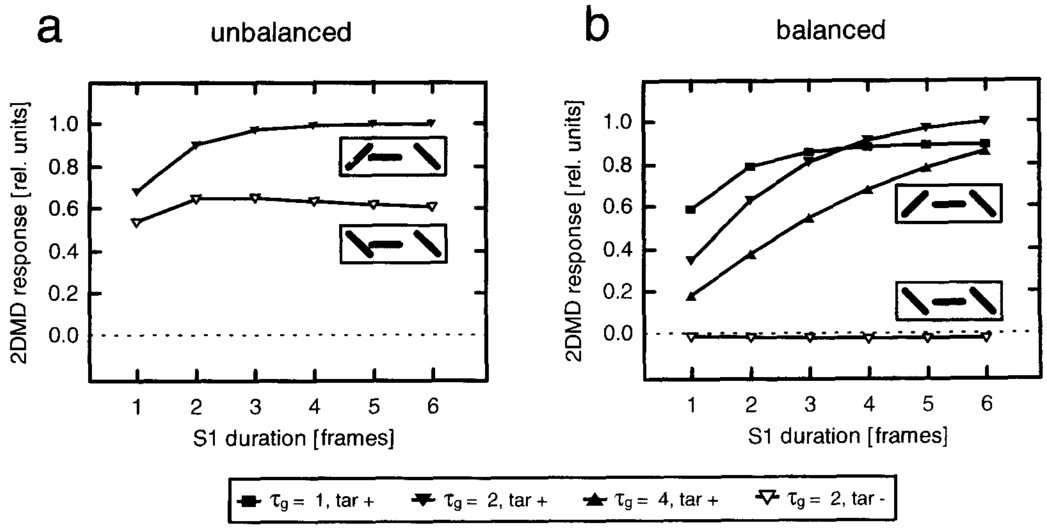


FIGURE 4. Maximum output of the 2DMD model for variations in the presentation time of the first stimulus image, with dynamic local gain control. Results are averaged for a given area of interest and normalised to the strongest response for each set of simulations. (a) The horizontal bar is unbalanced in the vicinity of the distractor (open triangles) or target (filled triangles) inducing element. Bar position $\Delta x = 12$ pixels; gain control time constant $\tau_g = 2$ frames. The effect of gain control slowly increases, whereas the response elicited by the distractor element is maximum at short durations. (b) The horizontal bar is balanced in the centre between two distractor (open triangles; tar+) or one distractor and one target (filled symbols; tar −) inducing element. Bar position $\Delta x = 19$ pixels. The motion induction effect builds up as determined by the time constant $\tau_g$, and no directional response is elicited by two distractor elements on either side.

contour. The localisation of motion signals, not only in motion induction but also for simple stimuli, is clearly an important question for future research.

An intriguing case of motion induction is observed when the appearance of the horizontal bar is not preceded by a dot of the same luminance, but instead a dot is switched off on one side of the bar while a second dot persists on the other side of the bar throughout the complete stimulus sequence (Hikosaka *et al.*, 1993b). The model without gain control proposed here would lead us to expect a motion signal away from the persisting dot, by combination of an ON- and an OFF-signal similar to the reversed-phi stimulus in apparent motion (Anstis & Rogers, 1986). For reversed-phi, the perceptual reversal for stimulus pairings of opposite sign can be overcome by the human visual system, and the correct motion direction can be recovered by second-order motion mechanisms (Chubb & Sperling, 1989) which rectify the ON- and OFF-inputs (Chubb & Sperling, 1988). Just as the human visual system can combine targets of opposite luminance polarity in second-order processing to yield apparent motion, moving objects can be defined by a variety of stimulus features such as texture, binocular disparity, colour, temporal frequency composition, local orientation, or motion itself (Cavanagh & Mather, 1989; Cavanagh *et al.*, 1989). In this respect, second-order motion perception, pre-attentive segmentation, and motion induction are very similar to each other, in the wide variety of effective stimulus features (von Grünau & Faubert, 1994). One can speculate as to whether the control of local gain, as some sort of "synoptic" processing which can exploit and integrate many types of visual information, is related to the mechanisms of second-order motion processing. It may be possible to bias balanced motion signals in general, simply by assuming a control of the local gain of the EMD input signals that is voluntary or driven by feature contrast. Indeed, there is evidence for motion perception which is based on attention (Cavanagh, 1992), and recently it was proposed that salience maps may serve as direct inputs to motion detectors (Lu & Sperling, 1995).

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