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Processing speed in the motion-induction effect

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Abstract. The motion-induction effect, where an illusory motion is perceived within a bar when it is shown next to a spot presented slightly earlier, was studied with respect to the idea that it is based on differential processing speeds between the two ends of the bar. First, by using just a bar with a luminance gradient, the existence of a motion illusion (gradient motion) within such a bar was demonstrated, presumably due to the different processing speeds of differential luminances. When such a bar was used in the motion-induction effect, it was shown to modulate, for short delays, the strength of the effect up or down, according to the direction of the gradient with respect to the position of the spot. When the same bar was used in the double-motion-induction effect (split priming), in which motion is usually away from the later spot, it totally determined the perceived direction of illusory motion, independently of gradient direction with respect to the later spot or the time between the two spots. These results demonstrate, on the one hand, that differential local processing speed is a likely mechanism to underlie the motion-induction effect. On the other hand, they also suggest the involvement of other more global (and perhaps top-down) processes.

1 Introduction

When a visual stimulus is suddenly presented to an observer, this constitutes a perceptual event which is accompanied by many phenomena and can last an appreciable amount of time. Even if the presentation is physically simultaneous for all parts of the stimulus, perceptually some part of the stimulus may be perceived before others. This has been well known to vision researchers for a long time, and has been described as gamma movement by the early Gestalt psychologists (Kenkel 1913; Harrower 1929; Newman 1934). It refers to the observation that an extended stimulus, when presented suddenly, appears to come on first in its center and then develop from there outward to its periphery, giving the sensation of motion within the stimulus.

While gamma movement is an effect of the presentation of a stimulus on the perception of the stimulus itself, the presentation of a stimulus also sets up particular conditions in its neighborhood that affect the perception of another stimulus presented subsequently in its vicinity. There are many phenomena that might be included in this description, but we will only be concerned here with two of them. First, prior presentation of a cue stimulus can change the perceived temporal order of two subsequent stimuli, one presented near the cue and the other presented at a distance from the cue (Stelmach and Herdman 1991; Hikosaka et al 1993a). The stimulus near the cue appears to be speeded up in its processing as compared with the more distant one. In a related situation, this can also lead to a reversal of the perceived direction of stroboscopic motion which is usually seen to go from the first to the second stimulus (Stelmach et al 1994). A second phenomenon, referred to as the line-motion effect (Hikosaka et al 1993a) or motion induction (von Grunau and Faubert 1994), describes the illusory motion within an extended stimulus away from the end that is closest to the stimulus that was presented previously. It appears as if the line or bar stimulus, even though presented all at once, grows from the end near the inducing stimulus until it subtends its full extent.

These phenomena are related and seem to involve local changes of processing speed, but the underlying mechanisms are still rather unclear. In one approach it has been proposed that involuntary and voluntary attention can account for both the illusory temporal order and the illusory motion (Hikosaka et al 1993a, 1993b). According to this view, a motion-detecting mechanism would receive signals from two spatial locations and give a direction-specific response if the signals arrive in a certain order. Attention is hypothesized to accelerate the processing of visual information coming from the location to which attention is directed. The effect of attention is further assumed to occur early enough so that it can feed into the motion-detecting mechanism and thus influence the order of arrival of the signals.

Other experiments have shown that the motion-induction effect occurs for stimuli defined by many attributes (such as luminance, color, motion, stereodepth, and texture) and must thus involve more than elementary motion detectors (von Grunau and Faubert 1994). Even-higher levels of processing are suggested by observations that visual forms affect motion induction (von Grunau and Faubert 1992) and that a learned cue position can result in motion induction (Faubert and von Grunau 1992b). Recent experiments combining motion induction and the visual-search paradigm suggest that there exist at least two different levels of facilitation which can cause motion induction: a lower automatic (preattentional) level and a higher attentional level (von Grunau et al 1994a). Thus there still remain controversies as to how early or late in the visual processing the effect occurs and whether it is basically bottom-up or top-down.

If indeed the motion-induction effect (or, at least, one type of this effect) depends on a change of processing speed, as suggested by some experiments, and if it involves differently timed inputs to some motion detector, then using other means of achieving timing differences of inputs to a motion detector would also produce a similar perception of illusory motion. Moreover, such an illusory motion could be expected to influence directly the illusory motion produced by motion induction, ie it might be able to cancel or reinforce it. One such means might be given by the fact that processing speed of visual stimuli depends on (among other things) the luminance of the stimulus: the less intense a stimulus is, the greater will be the processing latency (Roufs 1963; Wilson and Anstis 1969). It has been found that the delay increases with increasing difference in luminance and is greater with overall low luminance; a tenfold decrease in luminance gives a delay of about 20 ms and the maximum delay varies between 100 and 200 ms; the delay is localized to a particular position on the retina and cannot be a property of the eye as a whole.

These facts make it possible that a bar stimulus containing a luminance gradient would by itself result in a motion sensation away from the high-luminance end. This would be an illusory motion produced purely by differences in processing speed between the different parts of the bar. We could further hypothesize then that the use of such a bar stimulus within the motion-induction paradigm would influence the strength of motion induction if the two illusory motions are produced at the same (presumably early) motion detector.(1) That is, motion induction could be made stronger or weaker, according to whether gradient motion would occur in the same or opposite direction. In the present experiments, we investigated the existence of the gradient motion effect and its influence on motion induction in the two paradigms of simple-motion (one inducing spot) and double-motion (two inducing spots) induction (split priming; Faubert and von Grunau 1995). The main goal in this study was the following: given the inconclusive evidence for processing-speed differences in motion induction,

(1) Strictly speaking, an interaction between the two effects may also occur if they share only a later stage of processing. This point will be taken up in section 5.

we attempted to investigate how the known processing-speed differences associated with different luminances could affect the size of the motion-induction effect. We found that gradient motion can be demonstrated, and that it can influence motion induction under certain conditions.

2 Experiment 1: Illusory motion with a luminance gradient

Since we wanted to contrast illusory motion produced in the bar by the prior presentation of a spot (motion-induction effect) and motion produced by a luminance gradient in the bar, we needed first to show the existence of the latter effect (gradient motion). In this experiment, therefore, only a bar was presented, without the spot, and the direction of illusory motion within the bar with respect to the high-luminance end of the bar was assessed.

2.1 *Method*

2.1.1 *Stimuli.* The experiments were conducted on a Macintosh IIci computer with an Apple High Resolution RGB Monitor. The stimuli consisted of a horizontal bar with a height of 0.53 deg and a length of 5.3 deg. It appeared in the middle of the screen with a fixation cross centered 1.7 deg below the center of the bar. In the first experiment the bar was filled with one of two luminance gradients:

Gradient 0: the bar had a uniform luminance from end to end of either 0.51 cd m^{-2} (dark) or 78.7 cd m^{-2} (light). This uniform bar was used as a control stimulus, and the two different luminances were used in combination with different background luminances, the dark bar with a background of 78.7 cd m^{-2} and the light bar with backgrounds of 0.51 cd m^{-2} and 39.74 cd m^{-2}.

Gradient -1: the bar had a luminance of 78.7 cd m^{-2} at one end and a luminance of 0.51 cd m^{-2} at the other end. Luminance declined linearly from one end to the other.

The bars could be presented on three different backgrounds; all were uniform and had luminances of either 0.51, 39.74, or 78.7 cd m^{-2} (they were of black, grey, or white appearance, respectively). This also created different contrast conditions, so that the gradient bars had high-contrast and low-contrast ends which could or could not be the same as the high-luminance or low-luminance ends, respectively. This allowed us to examine the question of whether illusory motion effects were due to luminance or contrast differences. An example of a gradient bar on a dark background is shown in figure 1.

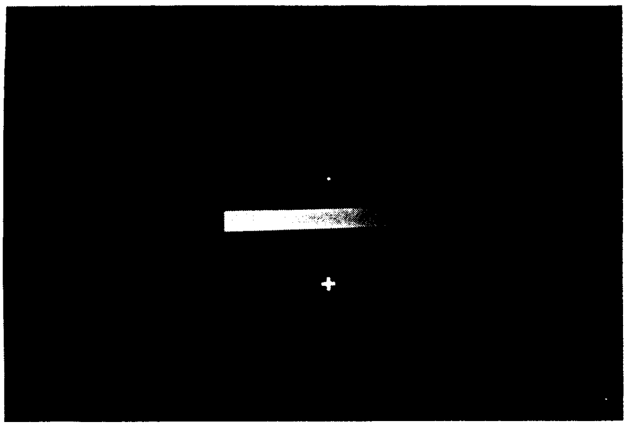

Figure 1. Example of a stimulus used in experiment 1. A bar with a luminance gradient is presented on a dark background. The gradient has a linear profile. An illusory motion is observed within the bar from the high-luminance end to the low-luminance end. Note that the high-luminance end is in this case also the high-contrast end.

2.1.2 *Procedure.* In this experiment, no spots were presented, only a bar. In an experimental trial, the bar appeared 500 ms after the uniform background with the fixation cross was displayed, and remained on to the end of the trial (ie until the subject responded, which usually occurred after between 0.5 and 1 s). The luminance gradient was presented in such a way as to have its high-luminance end randomly on the left or on the right an equal number of times. All conditions (gradient/background combinations, left/right gradient orientation) were presented twenty times in randomized order. Throughout each trial, the subject observed the computer display from a distance of 80 cm and fixated the cross below the stimulus display. After each trial the observer was asked to indicate the perceived direction of motion within the bar (left or right). The task was two-alternative forced choice, ie a choice had to be made even when there was no perceived motion (eg especially with the control gradient 0).

2.1.3 *Subjects.* There were five subjects, two of the authors (MvG and ZS), and three undergraduate students from Concordia University, who were naive as to the aim of the experiment. All had normal or corrected-to-normal vision (20/20 Snellen).

2.2 *Results and discussion*

Results were organized in terms of the percentage of responses in a particular direction (ie away from the high-luminance end for the stimulus with the gradient bar, and away from the left end for the stimulus with the uniform bar) for each of the conditions for each observer. These responses were submitted to a within-subject analysis of variance (ANOVA).

In figure 2a, the results are plotted for the two gradients as a function of the three background luminances. For the uniform control bar, about an equal number of responses indicated motion away from the left end and motion away from the right end, ie motion direction was not biased. As expected, the presentation of a uniform bar resulted only in gamma motion with no particularly preferred direction (Kenkel 1913; Kanizsa 1951). Subjects were forced, however, to choose one direction on each trial. When the bar contained a luminance gradient, on the other hand, perceived direction of motion was biased in such a way that there were significantly more responses for motion away from the high-luminance end. In the ANOVA, the effect of the type of gradient was significant ($F_{1,4} = 16.1$, $p = 0.016$); the effect of the background, however, not ($F_{2,8} = 0.09$, $p > 0.91$), nor the interaction ($F_{2,8} = 0.18$, $p > 0.83$). As can be seen in figure 2a, the results for the gradient bar on the dark background were

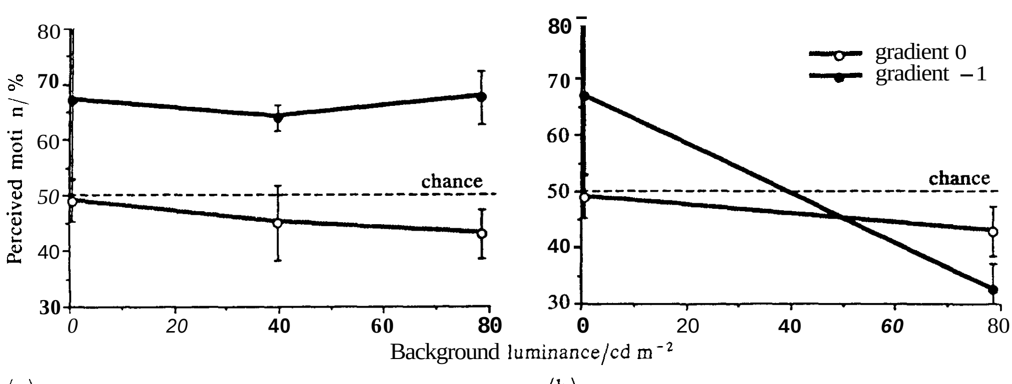

Figure 2. (a) Results of experiment 1, expressed as the percentage of perceived motion away from the high-luminance end of the gradient bar for three different backgrounds, and away from the left end for a control bar. (b) The same results for two backgrounds, plotted as the percentage of perceived motion away from the high-contrast end in the case of the gradient bar. All data are given as the means for five observers, with standard errors.

the most variable, and thus inhomogeneity of variance could render the effect of the type of gradient insignificant. Epsilon correction, however, did not change the results. The large variability for this condition was due to the responses of two of the observers. It is not known what caused this difference, but it was not related to the amount of their experience. Thus when the perceived illusory motion is interpreted to be away from the high-luminance end of the bar, the two gradients behave differently and background luminance does not affect the perceived motion. The location of the high-luminance end of the bar can thus be used to predict the direction of perceived motion.

Presenting a luminance gradient on different backgrounds also has the effect of forming bar ends that have high or low contrast with respect to the background. Thus the high-luminance end on a dark background would also be a high-contrast end, while the same end on a bright background would produce very little or no contrast. Since it is also possible that the illusory-motion experience was the result of the different-contrast ends of the gradient bar, the results were reanalyzed. The medium background was not included in the analysis, since it only produces two ends with equal contrast. The results of this analysis are presented in figure 2b for the two gradients as a function of the two background luminances. The outcome for the uniform bar, of course, remained the same: motion direction was not biased and did not differ for the two backgrounds. For the gradient bar, however, perceived motion was biased in the direction toward the high-contrast end for the dark background, and in the direction away from the high-contrast end for the bright background. Statistically, this resulted in a significant interaction ($F_{1,4} = 20.4$, $p < 0.01$), and nonsignificant gradient ($F_{1,4} = 0.17$, $p > 0.7$) and background ($F_{1,4} = 4.37$, $p > 0.1$) effects. Again, epsilon correction did not affect these results. This means that the location of the high-contrast end of the bar cannot be used to predict the direction of the perceived motion. This conclusion is reinforced by the fact that the gradient bar on a medium (grey) background resulted in a clear motion illusion in the direction away from the high-luminance end. Since both ends here had approximately the same contrast (but with opposite sign), no directional effect would be expected if amount of contrast were responsible.

In summary, this experiment demonstrated the existence of an illusory-motion experience in a bar containing a luminance gradient which is flashed on simultaneously over its whole length. It was also shown that this motion effect was the result of the luminance difference between the two ends of the bar and not of their contrast difference. With this information, we can now use the gradient bar together with the motion-induction effect.

3 Experiment 2: Simple-motion induction is little affected by gradient motion

In the simple-motion-induction effect, a spot is presented just prior to the bar near one end of the bar. Motion is perceived within the bar, usually in the direction away from the end of the bar nearer to the spot. The prevalence of this motion depends on, among other variables, the delay (SOA) between the onsets of the spot and the bar (Hikosaka et al 1993a). There is little effect for very brief SOAs, below about 40 ms. Then the effect increases with increasing SOA and remains fairly stable up to rather long SOAs (in the order of seconds). In this experiment, we attempted to influence the motion-induction effect positively or negatively by using the gradient motion effect, demonstrated in the first experiment.

3.1 *Method*

3.1.1 *Stimuli.* The stimuli consisted of an inducing spot next to one end of a horizontal bar. The spot was a square with sides 0.53 deg and the bar was a rectangle with a height of 0.53 deg and a length of 5.3 deg. They appeared in the middle of the screen with a fixation cross centered 1.7 deg below the center of the bar. The bar was filled with either one of the following gradients:

Gradient 0: the bar had a uniform luminance from end to end of 38.8 cd m^{-2} and served as a control stimulus.

Gradient -2: the luminance of the bar ranged from 78.7 cd m^{-2} on one end to 0.51 cd m^{-2} on the other end with an approximately exponential decay. Before this gradient was used, it was verified, in the same way as in experiment 1, that it also produced the illusory-motion effect. Motion away from the high-luminance end was found for 67.2% of the responses. This compares well with the result for gradient -1.

The luminance of the spot was 38.8 cd m^{-2}, and the stimuli appeared on a uniform dark background of 0.51 cd m^{-2}. An example of the gradient stimulus with the spot is given in figure 3.

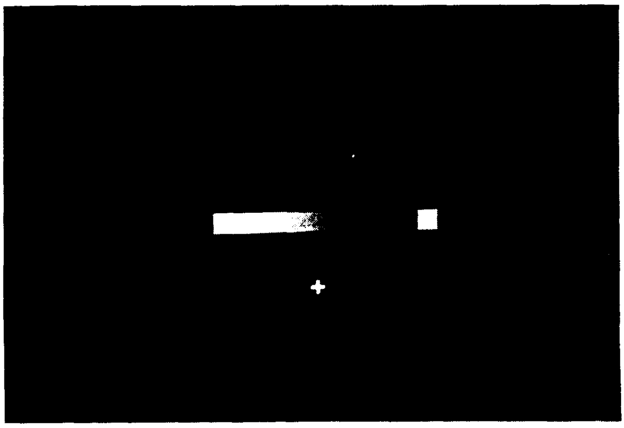

Figure 3. Example of a stimulus for experiment **2.** A spot and a bar with luminance gradient (nonlinear profile) are presented with a certain SOA. The spot could be next *to* either the high-luminance or the low-luminance end of the bar.

3.1.2 *Procedure.* In this experiment, the spot appeared 500 ms after the background with the fixation cross. It was followed after a variable SOA by the bar. The following SOA values were used: 0, 30, 60, 90, 120, 150, and 300 ms. Spot and bar remained on to the end of the trial. The luminance gradient was presented in such a way as to have its high-luminance end randomly on the left or on the right an equal number of times. As well, the spot appeared an equal number of times to the right or to the left of the bar. Thus the spot appeared an equal number of times next to the high-luminance and the low-luminance end of the bar. In this way, the effects of the spot and the luminance difference on the perceived illusory motion could be examined. In some conditions the two were opposed to each other, in other conditions they were in the same direction.

For each SOA, the spot was presented ten times next to the high-luminance end and ten times next to the low-luminance end in randomized order. Throughout each trial, the subject observed the computer display from a distance of 80 cm and fixated the cross below the stimulus display. The observer was asked to indicate the perceived direction of motion within the bar (left or right), the task being again a two-alternative forced-choice task.

3.1.3 *Subjects.* The same five subjects as in the first experiment also participated in this experiment.

3.4 *Results and discussion*

The results were organized in terms of the percentage of responses indicating motion away from the spot and analyzed with a within-subject ANOVA. They were averaged over the five observers and are presented in figure 4 for the following three cases: control bar, gradient bar with the spot next to the high-luminance end, and gradient bar with the spot next to the low-luminance end. They are displayed as a function of the SOA between the spot and the bar. For the control bar, the results resemble those reported previously (Hikosaka et al 1993a); only for the case in which spot and bar appeared simultaneously (SOA = 0 ms) was the perceived motion direction ambiguous. For all other SOAs, direction of motion was almost completely away from the spot and did not change as a function of SOA.

When the gradient bar was used and the spot and the high-luminance end were on the same side, ie when spot-induced and gradient-induced motion were expected to be in the same direction, there was a significant motion effect even for the zero delay (Tukey HSD, $p < 0.01$, compared with the control bar). For all other SOA, motion away from the spot was perceived practically 100% of the time. This indicates that when both illusory motions are allowed to work in the same direction, their effects can be additive.

When the gradient bar was used and the spot and the high-luminance end were on opposite sides, ie when spot-induced and gradient-induced motion were expected to be in opposite directions, motion away from the spot was perceived less often than for the control bar. This, however, was only the case for SOA values up to about 90 ms (statistically, only the outcome for 30 ms differed when compared with the control bar; Tukey HSD, $p < 0.05$). For longer SOA, motion away from the spot was again perceived on almost all trials. This indicates that when the two illusory motions oppose each other, their effects can be subtractive.

The ANOVA demonstrated a significant interaction between the three kinds of gradients and the seven SOA values ($F_{12,48} = 4.85$, $p < 0.0001$), a significant effect of SOA ($F_{6,24} = 13.77$, $p < 0.0001$), but nonsignificance for the gradients ($F_{2,8} = 4.24$, $p > 0.05$). This last result reflects the fact that all gradients show different results only at short SOA, while they are almost identical at longer SOA.

Because of the spatial (ie inside edge of the spot abuts the outside edge of the bar) and temporal (ie zero or small SOA) proximity, forward masking by the spot onto

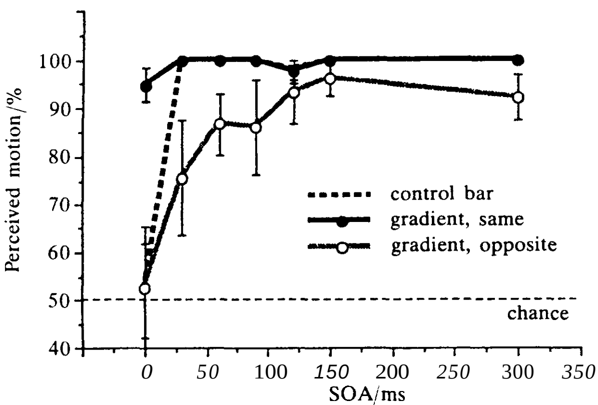

Figure 4. Results for experiment 2. Percentage perceived motion away from the spot is given as a function of the SOA between the spot and the bar for a control bar, for a gradient bar where gradient motion is in the same direction as motion induction, and for a gradient bar where gradient motion is in the opposite direction to motion induction. Results are given as the means for five observers, with standard errors.

the bar may be present, causing reduced visibility of this end of the bar. For the gradient bar ('same' condition), the visibility of the bright end would be reduced and thus the gradient motion effect would be decreased, ie the difference obtained here with the control bar would be an underestimation. For the gradient bar ('opposite' condition), the visibility of the dark end of the bar would be affected. But since it is already at zero contrast, this should not affect the perceived motion. Thus the presence of a forward-masking effect could not explain the obtained results.

In summary, motion induced by the spot determined for the most part the direction of perceived illusory motion of the combined stimulus containing the gradient. At short delays between the spot and the bar, however, the direction of the luminance gradient could modulate the strength of the observed motion induction. When it worked in the same direction, it increased the strength of motion induction. When it worked in the opposite direction, it decreased the strength of motion induction. The fact that this influence was present only for very short delays suggests that the effect of motion induction on processing speed takes some time to develop and can last for comparatively long durations, whereas the effect of the luminance gradient is present immediately and lasts only a much shorter time.

4 Experiment 3: Double-motion induction (split priming) is determined by gradient motion

The influence of luminance-gradient-induced motion on the strength of the motion-induction effect was relatively weak in experiment 2. Though it was clearly present (which is theoretically important, since it demonstrates that the two effects interact and thus share some processing), it amounted only to a modulatory effect at short delays between spot and bar. Simple-motion induction was used as the paradigm, where the facilitation effect operates in only one location. Previously, it was reported that motion can be induced by two or more spots simultaneously, but that in that case the strength of the effect seemed reduced (Faubert and von Grünau 1992a, 1995). For that reason, we used the split-priming paradigm, where the presentation of two inducing spots leads to the perception of two motions away from either spot which seem to collide somewhere in the middle of the bar. When the two spots are presented with a delay between them, motion is seen increasingly as away from the temporally second spot. In this situation, the gradient-induced motion might have a stronger effect on motion induction and it might be easier to cancel motion due to the priming spot by motion due to the luminance gradient.

4.1 *Method*

4.1.1 *Stimuli.* The stimuli were very similar to the ones used in experiment 2. They consisted of a horizontal bar and two spots, one next to each end of the bar. The stimulus dimensions and the location of the fixation cross were the same as in experiment 2. The bar was also filled with the same gradients as before (the control gradient 0, 38.8 cd m^{-2} throughout, and the test gradient -2, 78.7 cd m^{-2} at one end, 0.51 cd m^{-2} at the other end). The luminance of the spots was the same as that of the control bar (38.8 cd m^{-2}), and that of the dark uniform background was 0.51 cd m^{-2}. An example of the gradient stimulus with the two spots is given in figure 5.

4.1.2 *Procedure.* In this experiment, two spots were presented together with the bar. The first spot appeared 500 ms after the trial was initiated and was followed by the second spot after a certain stimulus delay. The possible values for this delay were: 0, 60, 120, 180, 240, 300, 1500, or 3000 ms. The SOA between the second spot and the bar was fixed at 300 ms. Spots and bar remained on to the end of the trial. When the two spots appeared simultaneously (stimulus delay = 0 ms), the usual percept with a homogeneous bar consisted of two illusory motions within the bar, one each

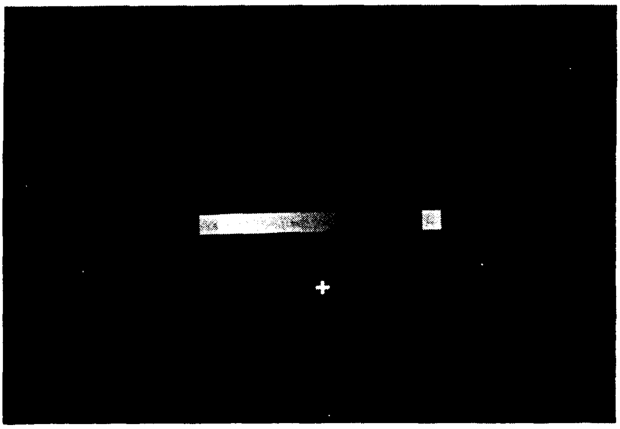

Figure 5. Example of a stimulus used in experiment 3, containing a luminance-gradient bar (nonlinear profile). The two spots were presented with a variable stimulus delay between them, followed by the bar with a SOA of 300 ms.

away from each spot. Often this had the appearance of a 'collision' near the middle of the bar. When the second spot was delayed (stimulus delay >0 ms), motion away from the second spot became dominant, the more so the larger the stimulus delay. Often it appeared as if the collision point was displaced toward the location of the first spot. Thus the second spot usually determines the direction of motion induction in this paradigm (Faubert and von Grunau 1992a, 1995). Observers were to indicate the dominant motion, either left or right in a two-alternative forced-choice task.

Conditions were presented randomly such that the second spot could appear equally often next to the left or the right end of the bar (the first spot being presented next to the other end). The luminance gradient was presented in such a way as to have its high-luminance end randomly on the left or on the right an equal number of times. In this way, the high-luminance end was next to the second spot 50% of the time, and 50% of the time the low-luminance end was next to the second spot. Since with non-zero stimulus delay the second spot determines the direction of the illusory motion, on half of the trials luminance-induced motion was in the same direction as motion induction, and on the other half of the trials in the opposite direction, allowing us to examine the relative effects of both kinds of motions on the overall illusory-motion percept.

For each stimulus delay, the second spot was presented ten times next to the high-luminance end and ten times next to the low-luminance end in randomized order. Throughout each trial, the subject observed the computer display from a distance of 80 cm and fixated the cross below the stimulus display.

4.1.3 *Subjects.* Four of the same five subjects as in the first two experiments (including the two authors) also participated in this experiment.

4.2 *Results and discussion*

The results were organized in terms of the percentage of responses indicating motion away from the second spot. They were analyzed by using within-subject ANOVA procedures. In figure 6a, the results are averaged over the four observers and displayed as a function of the stimulus delay between the two spots. They are given for the homogeneous control bar and for the bar containing the luminance gradient. For the control bar, responses were generally close to chance level for short stimulus delays, ie motion away from the second spot and motion away from the first spot were perceived about equally often, though there was a small bias for motion away from the second spot. This might indicate the percept of collision near the middle of the bar (perhaps somewhat closer to the first spot), since observers were forced to choose only one direction on every trial. It could also indicate that no motion was perceived within the bar, but previous research has shown unequivocally that a (more or less) central collision is perceived in this case (von Grunau et al 1994b; Faubert and von Grunau 1995). As stimulus delay increased, the proportion of responses for motion away from the second spot increased and then remained steady. This behavior would be expected from previous research (Faubert and von Grunau 1992a, 1995). The maximum level reached was only about 85%, which might indicate that even at long stimulus delays some motion away from the first spot was perceived. The possible conflict created by the presence of two opposing motions may also be reflected in the comparatively large variability in the results. Subjects may have found it hard to make clear decisions and thus produced noisy data by adopting different response criteria.

The results for the gradient bar are on the average a bit less variable, possibly indicating that these judgments were easier to make, since only one clear motion direction was experienced. The proportion of responses for motion away from the second spot remained close to chance level for all stimulus delays. This indicates that the position of the second spot had no influence on the direction of perceived motion, ie the motion-induction effect was possibly dominated by the luminance-induced motion, since the responses are averaged over the gradient direction. The ANOVA showed a significant effect only for the type of bar ($F_{1,3} = 17.47, p < 0.025$). Both stimulus delay ($F_{7,21} = 1.83, p > 0.13$) and the interaction ($F_{7,21} = 1.07, p > 0.42$) were not significant. This reflects the result that the two types of bar produced different responses for all stimulus delays.

When the results for the gradient bar are reanalyzed in terms of the percentage of responses away from the high-luminance end of the bar, with the position of the spots disregarded, the result is very clear (see figure 6b). This motion direction accounts for almost 100% of the observers' responses for all stimulus delays. The gradient direction therefore determined the illusory-motion direction for this stimulus.

In summary, the split-priming paradigm led to results that were very different from those with the simple paradigm of experiment 2. There the gradient motion could only slightly modulate the perceived illusory-motion direction, and only for short SOA. In contrast, in the present experiment the direction of the gradient totally determined the overall direction of the illusory motion. The influence of the spots,

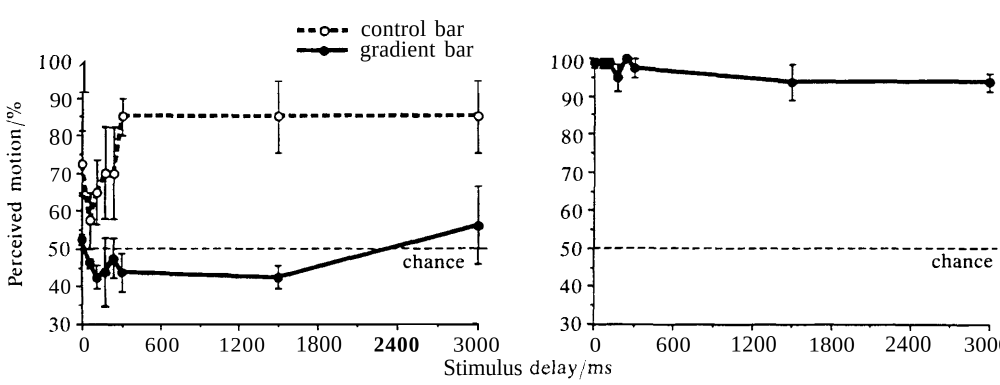

Figure 6. (a) Results for experiment 3 expressed as the percentage of perceived motion away from the second spot as a function of the stimulus delay between the two spots for a control bar and the gradient bar. (b) The same results for the gradient bar replotted as percentage of perceived motion away from the high luminance end. All results are given as the means for four observers. with standard errors.

though present for the homogeneous bar, was negated by the presence of the luminance gradient in the bar. Surprisingly, this effect was present over all stimulus delays, which spanned a large range of 3000 ms. The second spot, therefore, though able to induce motion in a direction away from itself (see control bar), ie to facilitate the bar end nearest to itself, has only a very weak effect that is easily overridden by the luminance-induced-motion effect.

5 General discussion

The main point in this study was to find evidence for the contention that the motion-induction effect could be based on differential processing speed between the end of the bar that is close to the inducing stimulus and the other end, far from the inducing stimulus, produced by the prior presentation of the inducing stimulus. Feeding these temporally modulated signals into a motion detector could result in the perception of (illusory) motion in the bar away from the inducing stimulus. We attempted this by examining the way in which the motion-induction effect can be influenced by another illusory-motion effect, which we called gradient motion. This effect, which consists of the perception of motion in a bar that contains a luminance gradient, with the direction of motion being away from the high-luminance end, is presumably based directly on the differential processing speed, created by the varying luminance along the length of the bar. The first issue that needs to be examined is this very assumption.

5.1 *Is gradient motion based on the luminance difference?*

Since the bar containing the luminance gradient has to be presented on some background, there also has to be an associated contrast difference between the two ends of the bar. We examined directly whether this contrast difference, rather than the luminance difference, could be causing the motion illusion. Our results make it clear that contrast could not have been the determining factor, but that luminance could account well for the observed motion direction.

A second possibility to explain the gradient motion is to invoke an explanation based on attention. The high-luminance end might have attracted attention, like the way the spot in motion induction may attract attention, and this might have caused the perceived motion, and not the differential processing speeds of the different luminances. If this were a valid explanation, one would expect that the high-contrast end of the bar would likewise attract attention and cause the illusion. As already pointed out above, however, the direction of motion could not be associated with the direction of contrast. We therefore conclude that the most likely explanation of the gradient-motion illusion has to be one based on the differential processing speeds of the different luminances in the gradient bar, which is founded on a well-documented fact in the literature (eg Roufs 1963; Wilson and Anstis 1969).

5.2 *Does gradient motion influence motion induction?*

Given our conclusion that gradient motion is directly based on processing speed, we would like to know whether it is able to alter the amount of motion induction, by either increasing or decreasing the occurrence of motion away from the spot. The results for the regular bar indicate, just as had been shown previously (Hikosaka et al 1993a), that the effect of motion induction takes a short time to develop to its full strength. This time is in the order of 100 ms. Our experiment with the gradient bar shows that the differential processing speeds implicated in the gradient motion can affect the strength of the motion-induction effect. This modulation can be in both directions (increasing and decreasing), depending on the direction of the gradient. But this influence can be demonstrated only as long as the motion-induction effect has not reached its full strength, ie only for short SOA (<90 ms). The positive effect can be shown only for even-shorter SOA because a ceiling is reached very quickly.

We can rephrase this outcome as indicating that the facilitatory effect of the spot takes a short time to develop fully, and that motion within the bar is therefore occasionally (but with decreasing frequency) perceived in the direction toward the spot. When the gradient bar is presented, the differential processing speeds due to the differential luminances take effect immediately, and so the effect on motion induction can be demonstrated immediately. Even though this influence of gradient motion on motion induction is small, its existence is of theoretical importance, since it demonstrates that motion induction can be influenced by presumably early effects on processing speed.

5.3 Is motion induction based on processing speed?

Can we account for this influence in terms of processing speed? A certain time after the presentation of the bar, signals from different parts of the bar will have progressed different amounts and will arrive at the motion detector at different times (giving rise to the motion sensation). When the facilitatory effect is weak (eg after short SOAs), the difference in arrival time at the motion detector will be small and variable, leading to some reports of motion in the direction toward the spot. With the gradient bar, another gradient of arrival times is produced which adds to the first one. Thus, the arrival-time differences can be increased (when the high-luminance end is near the spot), making it more likely that motion away from the spot is perceived. Similarly, arrival-time differences can be decreased (when the low-luminance end is near the spot), making it less likely that motion away from the spot is perceived. The assumption that differential processing speeds underlie the motion-induction effect, just as they are known to underlie the gradient-motion effect, therefore, can account parsimoniously for the observed influence of the gradient bar.

This argument, on the other hand, cannot prove that motion induction is based on differential processing speeds, as has been suggested previously (Hikosaka et al 1993a). The existence and manner of the influence of gradient motion on motion induction suggests, however, that very similar mechanisms underlie both effects. Since we can be pretty sure about the mechanism of gradient motion, it follows that motion induction is also likely to be based on differential processing speeds, produced in this case by the facilitatory effect of the spot presentation. The reason for this facilitation near the spot remains unexplained for the moment; we have been concerned here only with the form that this facilitation takes.

5.4 *Does motion induction occur early in the visual system?*

Since the mechanism of luminance processing is generally thought to be early in the visual system, it would follow that the motion-induction effect also depends on low-level sensory functions. On the other hand, the classic motion-induction effect is believed to depend on high-level, perhaps attentional, processes (Hikosaka et al 1993a; von Grunau and Faubert 1994; Faubert and von Grunau 1995).

While the results of the influence of gradient motion on the simple motion-induction effect can be easily and parsimoniously accounted for by early bottom-up processes (local speeding up of the signals before they are fed into a motion detector of the Reichardt type), the results of the influence of gradient motion on the double-motion-induction effect (split priming) cannot all be explained easily in such a way. It is true that, on first consideration, processing speed could generally be thought to be able to also account for most of the results concerning the perceived direction of illusory motion in this case. But a more careful examination of the results suggests that additional factors have to be postulated.

Let us take the case of the control bar when both spots are presented simultaneously. Since the time between the spots and the bar (SOA) was 300 ms, the effects of both spots on the bar have to be assumed to be at full strength (see experiment 2).

If we assume a nonlinear (eg exponential) decay with distance of the facilitatory effect of the spot, speed of processing would predict two motion sensations away from the ends (eg collision). When the second spot is turned on more than 300 ms after the first, the results suggest that the effect of the first spot has now disappeared or is very weak. One could postulate a decay of the facilitation that begins 300 ms after onset and takes about 300 ms to complete. In our experiment 2, we do not have data beyond an SOA of 300 ms (the effective SOA for the first spot is 600 ms in the present case). In pilot experiments with the present setup, we observed no decay of the motion-induction effect for SOAs up to 1200 ms. And Hikosaka et al (1993a) reported little or no decay for up to 4.8 s. Thus a passive decay is not likely to occur. A suppressive effect of the second spot on the first one that builds up to its full strength over 300 ms could explain the increasing dominance of the second spot as the stimulus delay between the two increases. This seems to necessitate some assessment of the overall stimulus situation, either by a global bottom–up process or a top–down process. At any rate, the suppression is not total, since some motion away from the first spot is still observed (see figure 6a).

When a luminance gradient is present in the bar, gradient motion is always dominant, even when the spots are simultaneous. No collision is observed. This again could be explained simply by local processing speed alone. When there is a stimulus delay between the two spots, and the suppression effect of the second spot is assumed, processing speed could also account for the dominance of the gradient motion. The gradient motion effect, however, would have to be relatively strong with respect to the facilitation effect of the spots. In experiment 2, this was apparently not the case, since gradient motion only had a modulatory effect and only at short SOA (< 100 ms). If suppression of the spots were mutual (with the second one having a larger effect), then the resulting facilitation in the split-priming paradigm would be overall weaker, so that the normally small gradient motion effect could now have a powerful influence, even if it has to work against the direction of the motion induced by the second spot.

5.4 *Is attention involved in motion induction?*

At the end of this discussion one is left with the need to postulate that the motion-induction effect involves, in addition to the general facilitatory effect, suppressive effects between different inducing stimuli that interact with the facilitation on a more global level. This necessitates specific knowledge of the mechanism causing the facilitation in the first place. It could simply be that the presentation of a stimulus sets up an automatic sensitization of this area and adjacent regions, which shows itself as an increase in processing speed for stimuli presented subsequently in this neighborhood. A second stimulus (as in the double motion induction) would set up interactive (suppressive) effects between the two regions. It has also been suggested that attention could be the general underlying factor, which causes the increase in processing speed (Hikosaka et al 1993a). In the case of double motion induction (split priming), a split of attention must be assumed or a shift of attention from the first to the second stimulus (Faubert and von Grunau 1995). With the present experiments, however, we cannot discriminate between these possibilities, nor can we resolve the questions of where the effect is produced (early vs late) or whether it is mainly bottom–up or top–down. More recent experiments (von Grunau et al 1994a) provide evidence that both automatic and attentional factors are involved in the motion-induction effect.

6 Summary and conclusions

Together these experiments provide the first evidence that a mechanism that is based on processing speed is likely to have an important function in the creation of the illusory motion in the motion-induction effect. This follows from the way in which the motion-induction effect can be influenced by gradient motion. At the same time, however, it was also suggested that an early, local, bottom–up process based on processing speed alone cannot account for all our findings. More global, perhaps top–down, processes also seem to be involved in certain situations, revealed by the effect of gradient motion on motion induction with two inducing spots. The completeness of the dominance of gradient motion in this case is remarkable and needs an elaboration of the facilitatory mechanism.

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