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Intraattribute and interattribute motion induction

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Abstract. The phenomenon of motion induction occurs, for example, when a bar that is presented next to a spot, which itself was presented slightly earlier, is not correctly perceived to appear everywhere simultaneously, but seems to grow out of the spot. The spot is said to prime one end of the bar. Experiments have been designed to throw more light on the local and global aspects of this phenomenon, in particular to establish whether this illusory motion percept can be observed when the spot and the bar stimuli are defined with respect to the background by one of a variety of attributes, such as luminance, color, stereodepth (crossed and uncrossed), texture, and motion (start and stop). It was found that all attribute combinations supported motion induction readily, but that the strength of the perceived motion (as measured by magnitude estimation) varied and depended more on the attribute defining the bar than on the attribute of the spot. Luminance and color gave the most vivid effects, whereas motion and depth showed the least vivid effects. The influence of the amount of luminance and color contrast on the strength of the effect was also determined and it was found that these variables affected motion induction most at very low contrast levels close to detection threshold. It is concluded that the illusory motion in this effect depends only slightly on the particular visual attribute channel that carries the stimulus information. This is consistent with the contention that it is a high-level, attention-related effect, phenomenologically similar to polarized gamma movement.

1 Introduction

In the history of the investigation of motion perception, the study of various forms of illusory motion has played a very important role. The seminal papers by Wohlgemuth (1911) and Wertheimer (1912) have each inspired generations of researchers to study the mechanisms of motion processing through the illusions of the motion aftereffect and the phi phenomenon, respectively. Over the years, many other illusions of motion have been discovered and have contributed to our growing understanding of the underlying mechanisms. Another early discovery was gamma movement, which was first studied in detail by Kenkel (1913). Its definition is often given as the expansion or contraction of an object as the illumination is respectively increased or decreased (eg Boring 1942). Many aspects of this illusory movement within a flashed object were examined by Harrower (1929) and Newman (1934).

An interesting extension of gamma movement was introduced by Kanizsa (1951, 1979), who studied some aspects of the 'polarization' of gamma movement. This effect occurred when there was a second, permanently displayed stimulus near the one that was suddenly turned on (or off) to produce gamma movement. The perceived movement was now away from (or toward) the permanent stimulus, rather than the original expansion (or contraction).

More recently, a similar phenomenon was reported by Hikosaka et al (1991, 1993a). Here, the basic paradigm was to present a spot stimulus and to follow it after a short delay [stimulus onset asynchrony (SOA) > 40 ms] by the presentation of a bar, leaving the spot together with the bar. The result was a very vivid perception of movement within the bar, away from the spot. The bar appeared to be painted onto the screen, beginning at the end nearest to the spot and continuing smoothly toward the other end. In reality, the bar was flashed on the screen everywhere simultaneously (see figure 1a). We will call this kind of phenomenon motion induction, and would like to emphasize that it is not unique to a bar, but occurs more generally with a wide variety of objects (von Grünau and Faubert 1992b). It is manifest regardless of the orientation of the bar, and is not crucially dependent on the sizes of spot and bar or their separation, within limits. We noticed furthermore that, when the bar is then turned off (again simultaneously across its full length), it appears to retreat or be 'sucked back' toward the spot, which has remained on the computer screen the whole. time. This implies that the effect of the spot is fairly long lasting. Higher-level, perhaps attentional, influences have also been implied by much of the work of Shimojo and coworkers (Hikosaka et al 1991, 1993a; Miyauchi et al 1991, 1992), as well as by us (Faubert and von Grunau 1992, 1994). This work has shown that the effect occurs also across modalities and with imagined spot locations. Therefore, we have referred to the effect that the spot has on the bar as attentional priming. The importance of both lower-level and higher-level determinants for the effect, however, is not clear at this time. The existence of cross-modality motion induction by itself does not tell us much about the underlying visual mechanisms. In this paper, therefore, we wanted to explore the role of some lower-level visual parameters on the existence and strength of the motion-induction effect.

In previous studies, the stimuli were all defined with respect to the background by a luminance difference. The main point in the present experiments was to show that the motion-induction effect in the visual domain also occurs for stimuli defined by attributes other than luminance, ie when there is no luminance contrast between the

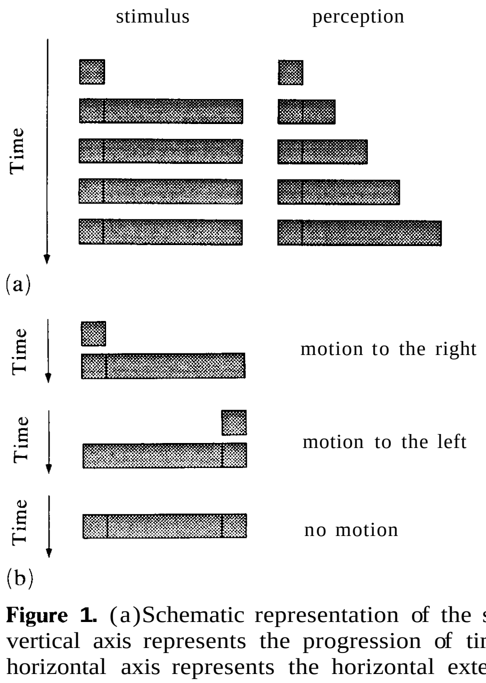


Figure 1. (a)Schematic representation of the stimulus sequence and the perceptual result. The vertical axis represents the progression of time and the vertical stimulus dimension, and the horizontal axis represents the horizontal extent of the stimuli. A spot is presented first and remains on throughout the experimental sequence. A short delay after the onset of the spot, a bar is presented and remains on. Perceptually, however, the bar does not appear everywhere simultaneously, but seems to grow out of the spot. (b)Schematic representation of the three test arrangements. The spot could be to the left of the bar, to the right of the bar, or spots and bar could appear at the same time. In the last (control) arrangement, the bar is slightly shorter to preserve a constant overall length of the display.

stimuli and the background. In the present experiments, we investigated motion induction when the inducing spot and the bar were defined with respect to the background by one of a variety of attributes, such as luminance, color, stereodepth (crossed and uncrossed), motion (start and stop), and texture. When the spot and the bar were defined by the same attribute, we had intraattribute motion induction, and when the spot and the bar were defined by different attributes, we had interattribute motion induction. This allowed us to examine the possible origin of the effect. We found that motion induction occurred readily for all intraattribute and interattribute conditions, but showed qualitative differences for the various attributes. We conclude that motion induction is not restricted to a particular visual-attribute channel, but is nonetheless influenced by low-level visual processes.

2 Experiment 1: Occurrence of intraattribute and interattribute motion induction

Even though motion induction is a very easily observable phenomenon, it is not easy to assess quantitatively. The illusory motion in the bar is very fast, so that a cancellation technique with real or sampled motion to oppose the motion-induction effect, cannot work when monitors with refresh rates of 15 or even 7.5 ms are used. Miyauchi et al were able to employ a cancellation technique, but only by using an oscilloscope for the display. This is fine for luminance stimuli, but is completely inadequate for the kind of stimuli that we wanted to use, where we needed to control luminance, color, and moving texture elements. In the first experiment, we examined only the readiness with which observers would report motion induction for the various intraattribute and interattribute combinations. In the second experiment, we used a magnitude-estimation technique to measure quantitatively the strength of the motion-induction effect.

2.1 *Method*

2.1.1 *Stimuli.* The experiments were conducted with a Macintosh IIci computer with the Apple high-resolution color monitor. The inducing spot was a square with 1.5 deg sides, and the bar was a rectangle of 1.5 deg by 7.5 deg. They appeared in the middle of the screen with a fixation cross centered approximately 7 deg below them. Many values for the SOA between spot and bar were examined in pilot experiments, and motion induction was found to occur over a large range (50 to 1000 ms), in agreement with the results of Hikosaka et al (1993a). For the formal experiments, SOA was fixed at 150 ms for luminance and texture and at 300 ms for color, depth, and motion. The observers watched this display from a distance of 57 cm, keeping their eyes on the fixation cross.

For the basic luminance and color conditions, the spot, bar, and background areas consisted of homogeneous luminance and color. The equiluminance points for each color combination used were determined for each observer separately by flicker photometry just prior to the experiment, with a display similar to the one used for motion induction. In extensive pilot experiments, we examined motion induction for a variety of luminance and contrast conditions, ranging widely and containing the values chosen for the formal experiments. In the experiments, the luminance for the background and the stimulus spot and bar was kept constant at 7.8 cd m^{-2} (there was no luminance contrast), except when the stimuli were determined by luminance. In that case, luminance-defined stimuli had an incremental contrast of 0.25.

Different isoluminant color combinations were tried in pilot experiments (see figure 2 for details): red/green (color 0 and color 120; these numbers refer to the angular representation of a given color derived from an HSV color space), blue/yellow (color 240 and color 60), and two blues (color 240 and color 260). For the formal experiments, color contrast was created with isoluminant red stimuli

($u' = 0.416$, $v' = 0.526$) on a green background ($u' = 0.183$, $v' = 0.550$). Contrast was calculated as $(\Delta u'^2 + \Delta v'^2)^{1/2}$, where $\Delta u'$ and $\Delta v'$ indicate the differences between the u' and v' values for the two colors. This resulted in a color contrast of 0.23. For the color/luminance combinations, isoluminant red and darker green stimuli were presented on a lighter same-green background with the appropriate luminance contrast.

For stereodepth, motion, and texture conditions, the three areas were filled with random dots with a density of 0.5 and a granularity of 1 pixel (corresponding to 2.2 min arc). Mean luminance of all these stimuli was constant at 7.8 cd m^{-2} across the regions of the background, the spot, and the bar. Depth was created in red/green anaglyph form and observed through appropriately colored glasses. A disparity of 11.1 min crossed or uncrossed was used. For motion conditions, drift velocity was 1 pixel per frame (corresponding to 2.44 deg s^{-1}). Drift direction was always perpendicular to the direction of motion induction. For the texture conditions, the two granularities used were 1 pixel and 2 pixels (2.2 min and 4.4 min, respectively). For the intraattribute conditions, both the spot and the bar were defined by the same attribute.

For interattribute conditions in general, parameters were adjusted so as to allow the proper combination of the two attributes. For example, for a luminance-defined spot and a motion-stop-defined bar, the whole field was filled with random noise drifting upward or downward. When the spot appeared, the random noise would continue to move within the area of the spot, while in addition a stationary luminance patch marked the spot, which now still consisted of drifting random noise but with a higher average luminance. The noise within the bar area would then stop drifting after the usual SOA, while the background continued to move. Thus the spot differed from the background only in terms of luminance, the bar only in terms of motion. In similar ways, all the other attribute combinations were created. Average luminance was kept constant at 7.8 cd m^{-2} for random-dot, luminance, and color areas. To illustrate better our stimuli, two reproductions are shown in figure 3.

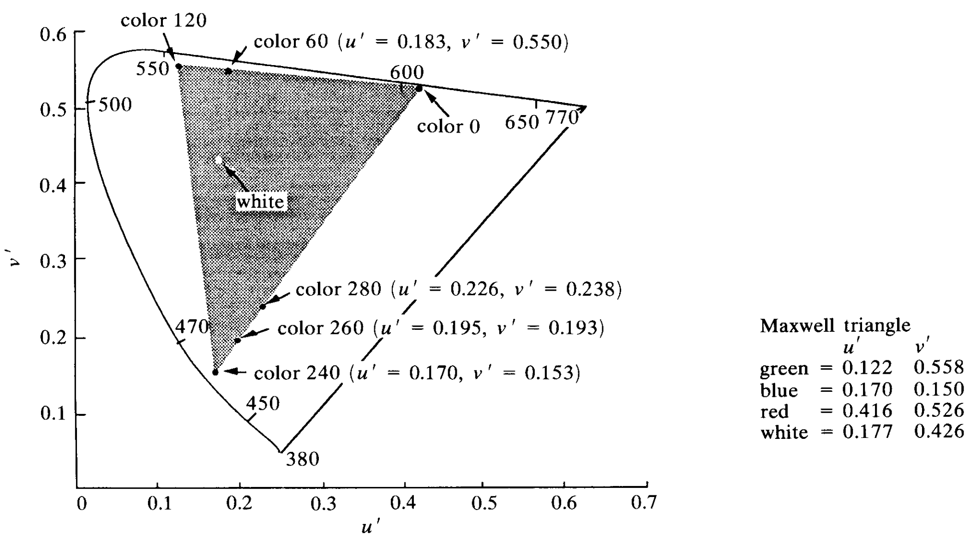
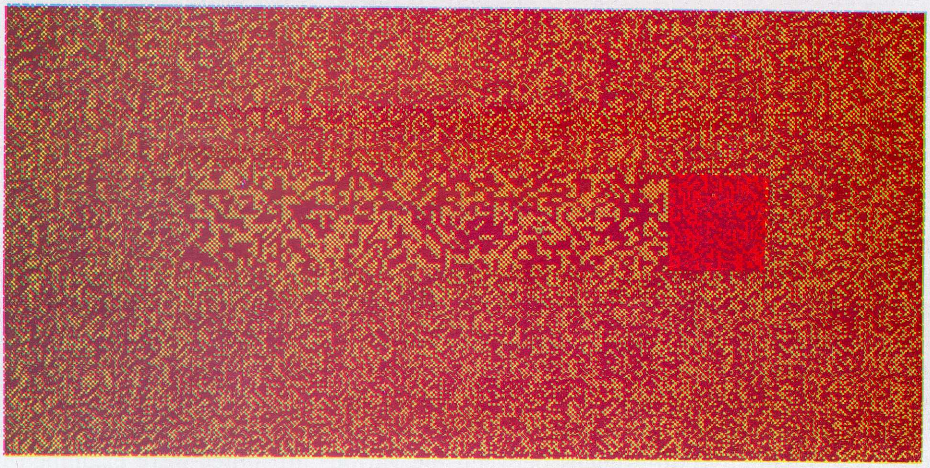
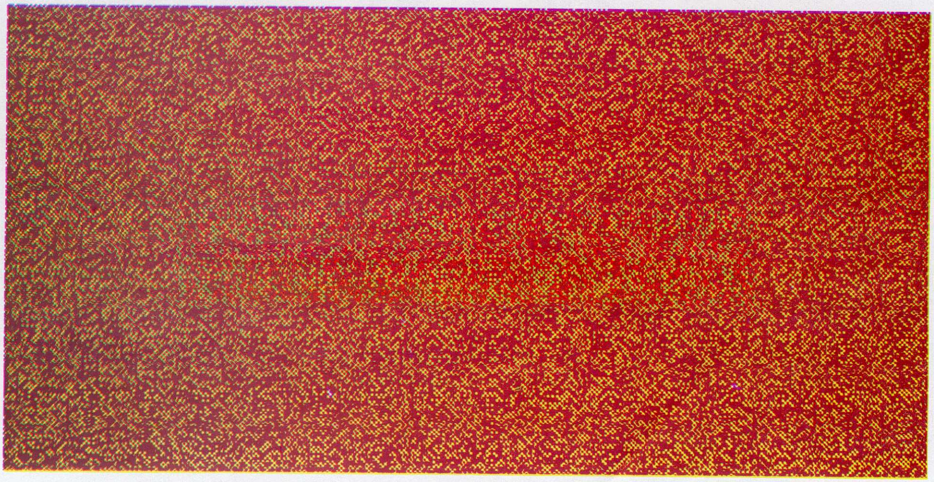


Figure 2. CIE 1976 ($u'v'$)-chromaticity diagram, illustrating the color space of our monitor (Maxwell triangle). Values for the red gun (color 0), the green gun (color 120), and the blue gun (color 240), and for white are given. The location and $u'v'$ values for other colors that were used in the experiments are also marked.

2.1.2 *Procedure.* The spot could be presented to the left or to the right of the horizontal bar, or the bar could be presented simultaneously with two spots (see figure 1b). The last was a control condition in which no motion induction was perceived, though there was some gamma movement expansion. These three test arrangements were presented an equal number of times in a randomized order, and the observer had to indicate leftward, rightward, or no motion for each trial. This is not a forced-choice technique, but the "no motion" response was there to allow the observer to report when there was actually no directed illusory motion. Observers were instructed to use this category when there was no rightward or leftward motion within the bar. Typically, sixty trials were recorded per condition for each observer.



(a)



(b)

Figure 3. Two examples of the stimuli used in our experiments. The background is not shown in its full extent. (a) A spot defined by color, combined with a bar defined by texture. (b) A spot defined by stereodepth (crossed disparity), combined with a bar defined also by stereodepth (uncrossed disparity). To be viewed through red/green stereo glasses.

2.1.3 *Subjects.* The observers consisted of one of the authors (MvG), two observers who were experienced psychophysical subjects but who were naive as to the aims in this study (MK, SD), and one who was not experienced (MA). All had normal or corrected-to-normal vision (20/20 Snellen, no errors on the Ishihara plates and the TNO stereo test).

2.2 *Results and discussion*

Results are given as percentage correct, based on the number of correctly perceived motion direction out of a total of sixty presentations (twenty for each of the three test arrangements). The correct direction was defined as the direction away from the spot (eg leftward motion when the spot was to the right of the bar) or no motion for the control arrangement. Results are reported separately for each observer.

2.2.1 *Intraattribute conditions.* Results are plotted for all seven attributes on the 135° diagonal in figure 4. Attributes defining the spot are listed on the right, those defining the bar along the bottom. Motion induction was almost perfect for all observers in all conditions, except for one observer in the motion-start condition, ie when stimuli were defined by the onset of random-dot motion within the spot and bar areas. In this case, the observer often did not perceive the motion away from the spot, but perceived no motion at all. The motion direction was never toward the spot for any observer.

The results clearly demonstrate that motion induction was possible for all tested attributes. This is not to say that it was qualitatively the same for all conditions. We noticed great differences in the 'goodness' (distinctness) and the perceived speed of the motion. The two motion conditions (motion-start and motion-stop) were generally the most difficult ones in the sense that the motion sensation was weakest. When there were mistakes, motion was never perceived in the opposite direction, the bar simply did not seem to contain any directional motion (as in the control arrangement). These qualitative differences between the various attributes were examined in experiment 2.

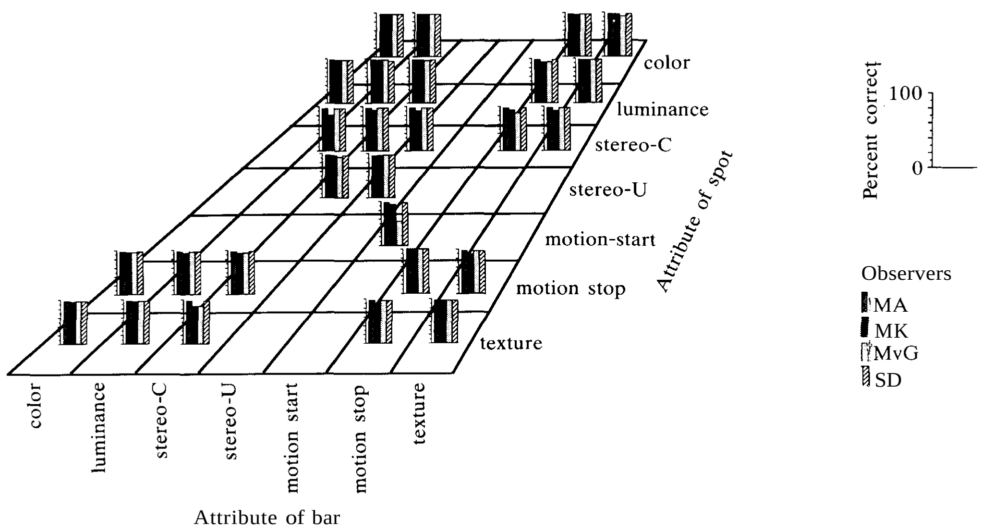


Figure 4. Results for all tested intraattribute and interattribute conditions, the intraattribute conditions being on the left-oblique diagonal. Percentage of correctly perceived motion induction is shown for four observers. Spot attribute is plotted on the z-axis, bar attribute on the x-axis. Note: stereo-C and stereo-U, stereodepth with crossed and uncrossed disparity, respectively.

2.2.2 *Interattribute conditions.* Figure 4 also shows the results for all other tested combinations of the attributes. Each cell corresponds to the intersection of a spot and a bar attribute, and for tested combinations the cell contains the percentage of correct responses from four observers. Certain combinations could not be tested, such as color in combination with stereodepth (stereo-C or stereo-U for crossed and uncrossed disparity, respectively), because of the way in which stereodepth was created. Others could have been tested, such as certain combinations with stereo-U or motion-start, but we did not expect any significant differences as compared with the results with stereo-C and motion-stop.

Results show that the motion-induction effect was present without exception for all tested conditions. That is, a spot defined by any one of the five attributes can prime a bar defined by any of the five attributes to produce motion induction. The resulting effects were equally prominent, but seemed to differ in quality. Some were very weak (eg those produced in a motion-defined bar), giving only an impression of directional movement without much form character to it. Others were very strong (those produced in bars defined by luminance or color), where the bar clearly appeared to be painted from one side (closest to the spot) to the other (farthest from the spot). It generally appeared that the attribute defining the bar was the one that dominated in determining the quality of motion induction, while the attribute defining the spot was of minor importance in this respect.

3 Experiment 2: Strength of motion induction

The results of experiment 1 showed that, as far as the occurrence of the motion-induction effect is concerned, the kind of attribute that is being used to define the stimuli with respect to the background is not of major importance. In all cases, intra-attribute or interattribute, the effect was observed very readily. It was obvious, however, that the quality of the effect was not at all equivalent in the different conditions. We therefore tested all conditions again, using a magnitude-estimation technique to assess the strength of the illusory motion.

3.1 *Method*

3.1.1 *Stimuli.* The stimuli were the same as in experiment 1, except that SOA was fixed at 300 ms for all conditions and that luminance-defined stimuli had a decremental contrast of 0.33.

3.1.2 *Procedure.* A magnitude-estimation technique (Stevens 1956) was used. In one series, all seven attributes were tested in intraattribute arrangements, ie spot and bar were defined by the same attribute. In a second series, only five attributes (luminance, color, stereo-C, motion-stop, and texture) were tested in all possible interattribute combinations of spot and bar (twenty-three conditions, since color and stereodepth could not be combined). In each series, every condition was presented several times in randomized orders (five times for series 1 and three times for series 2). The magnitude-estimation technique consisted of presenting first a standard stimulus. This was done at the beginning of each of the five (for series 1) or three (for series 2) runs. The standard was a textured stimulus for both spot and bar, with a granularity of 4 pixels (corresponding to 8.8 min arc). This stimulus was different from all the others and was not used in the reported data. The observer was told that this standard stimulus had a value of 20. This was followed in each run by all the experimental stimuli in some random order. On each occasion of a given experimental stimulus, the motion-induction display was presented five times, randomly with the spot on the left or the spot on the right. There was no control condition (simultaneous presentation of two inducing spots and the bar) as in experiment 1. Only after these five presentations was the observer to make a judgment. The observer was told to remember that the standard had a value of 20 and to assign a number to the first experimental stimulus, comparing its strength to that of the standard. Then the observer was to compare each of the following stimuli to the one just preceding, not anymore to the standard (eg the second to the first, and the seventh to the sixth). If the first experimental stimulus was perceived to generate a motion-induction effect whose strength was twice that of the standard, then it should receive a magnitude of 40. If the next one (stimulus N) was perceived to be only one quarter as strong as the preceding one (stimulus $N-1$), then in this case it was to be given a magnitude of 10. In this way, all stimuli were connected to the standard, but the observer did not have to remember the standard through the run. The experimenter entered the observers' responses into the computer and aided the observers if they had forgotten which number had been assigned to stimulus N-1.

3.1.3 *Subjects.* The same four observers as in experiment **1** participated in this experiment also.

3.2 *Results and discussion*

Since the same standard was used for all the measurements and for all observers, no standardization of the responses was necessary.

3.2.1 *Intraattribute conditions.* The results are shown in figure 5a. Magnitude estimates were averaged over the five estimates that were obtained for each condition within each observer, and were then averaged for the four observers. They are plotted as a function of the various conditions with standard-error bars. The size of the standard is indicated as the horizontal line at 20. There were clear differences between the conditions, which are analyzed with a simple ANOVA. The condition effect was significant ($F_{6,18} = 11.44$, $p < 0.00001$). A posteriori analyses showed that the attributes of luminance and color gave significantly stronger illusory motions than all the other attributes ($p < 0.05$), which were not significantly different from each other ($p > 0.05$).

3.2.2 *Interattribute conditions.* Corresponding results for the interattribute conditions are shown in figure 5b. Again, results for the three presentations for each condition were averaged for each observer, and the observers' results were then averaged. For this figure, the results were also averaged over the five attributes that determined the bar for those columns coded as spot, and over the five attributes that determined the

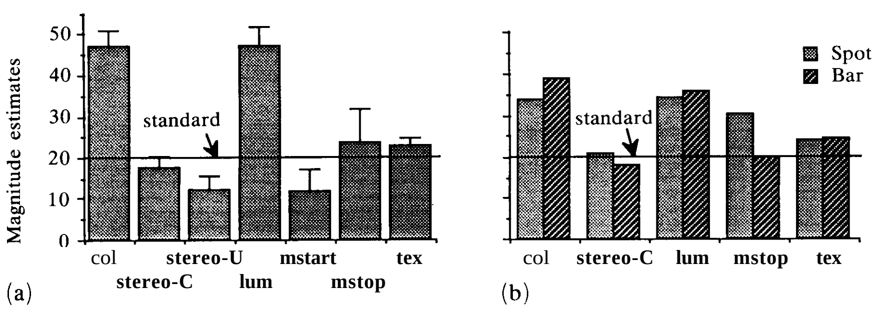


Figure 5. Results for the measurement of the strength of the motion induction effect. Magnitude estimates for (a) intraattribute and (b) interattribute conditions are given with respect to a standard at a value of 20. In (b) the effect is shown for each attribute when it defined the spot (averaged over all bar attributes) or the bar (averaged over all spot attributes). Standard-error bars are given only for (a), since the different values in (b) were obtained by averaging over different data sets. Note: col, color; lum, luminance; mstart, motion-start; mstop, motion-stop; tex, texture; stereo-C and stereo-U, stereodepth with crossed and uncrossed disparity, respectively.

spot for those columns that are coded as bar. For this reason, no standard-error bars are given in this figure. These overall effects for spot attribute and bar attribute were statistically significant (ANOVA; $F_{4,12} = 8.7$, $p < 0.002$ and $F_{4,12} = 6.8$, $p < 0.005$, respectively). Varying the bar attribute resulted in larger changes than variation of the spot attribute. One can readily see again that the attributes of luminance and color gave the highest estimates when these attributes were used either for the spot or for the bar. The simple effects are presented in figures 6a–6e in terms of the magnitude estimates as a function of the bar attribute for the five spot attributes, and in figures 6f–6j similarly as a function of the spot attribute for the five bar attributes. In both cases, only those variations where the spot or bar attribute was either luminance or

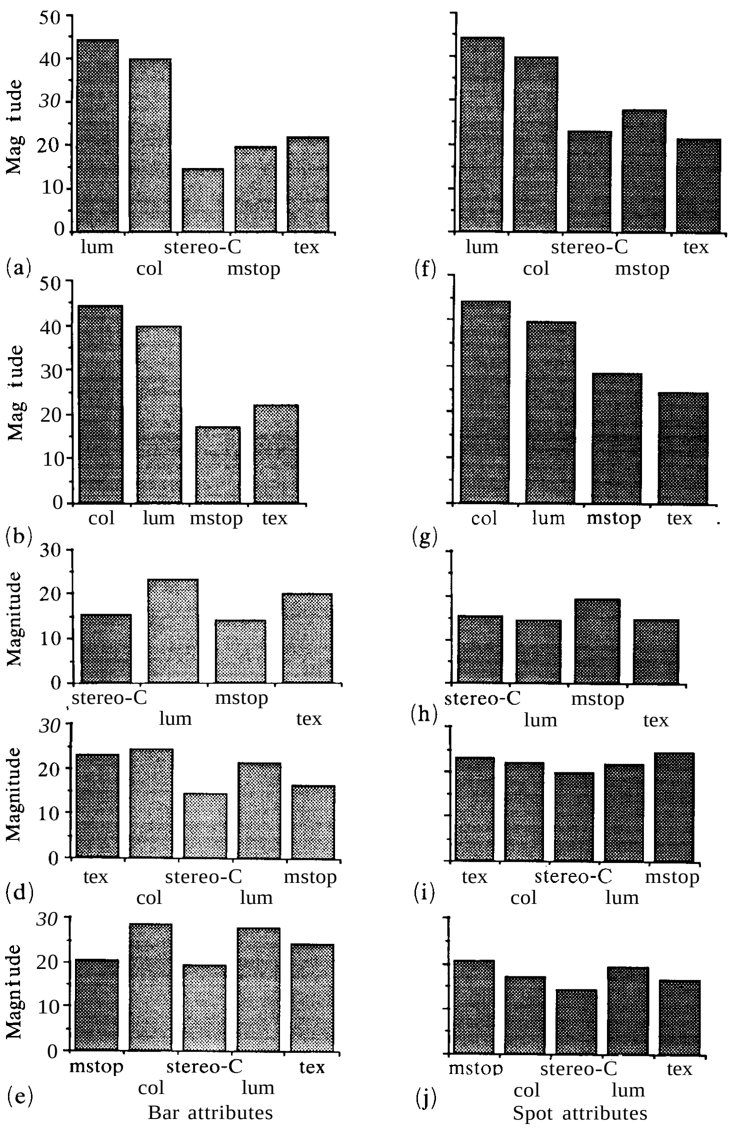


Figure 6. The simple effects (a–e) of varying the attribute of the bar for the various spot attributes and (f–j) of varying the attribute of the spot for the various bar attributes. The attributes were (a) and (f) luminance, (b) and (g) color, (c) and (h) stereo-C, (d) and (i) texture, (e) and (j) motion-stop. Note: lum, luminance; col, color; mstop, motion stop; tex, texture; stereo-C, stereodepth with crossed disparity.

color were statistically different ($F_{4,12} = 15.3$, $p < 0.0001$ for spot attribute luminance; $F_{4,12} = 11.0$, $p < 0.0006$ for bar attribute luminance; $F_{3,9} = 16.1$, $p < 0.0006$ for spot attribute color; $F_{3,9} = 13.0$, $p < 0.0015$ for bar attribute color).

4 Experiment 3: The influence of luminance and color contrast

In the first two experiments, we found that all attribute combinations resulted in readily perceived motion-induction effects. In addition, the use of magnitude estimation allowed us to compare the strength of the effect for different attributes. Even though this comparison allowed us to demonstrate the existence and differential strength of the motion-induction effect for different attributes, it is, however, limited to the specific parameters that were used to define the stimuli within the various attributes. The general problem that we encounter here is that we are not able to know the equivalence between the contrasts used within each attribute. That is, how can one compare a luminance-defined stimulus with a certain luminance contrast with, for instance, a motion-defined stimulus with a certain motion contrast or a color-defined isoluminant stimulus with a certain color contrast? In experiment 3, therefore, we pursued this question for the attributes of luminance and color. To this end, we varied the amount of luminance or color contrast for luminance-defined or color-defined stimuli. The rationale was the following. If the strength of motion induction does not vary much with the amount of contrast within a particular attribute (here luminance or color) over a wide range of contrasts, then it would be easier to make comparisons between those two attributes. This is because then, within limits, the particular amounts of contrast used for the stimuli in those two attributes become less important, and thus comparisons would be more meaningful. In the present experiment, we examined the influence of contrast on the strength of the motion-induction effect for two of the attributes used in our experiments, luminance and color.

4.1 *Method*

4.1.1 *Stimuli.* The stimuli were the same as in experiment 1, except that SOA was fixed at 300 ms for all conditions in experiment 3. For luminance-defined stimuli (equal color) and for color-defined stimuli (equal luminance), we examined how the motion-induction effect depended on the contrast between the stimuli and the background. For luminance, the background remained at a constant luminance (57 cd m^{-2}), while the luminance of spot and bar was varied to produce Michelson contrasts between 0.02 and 0.37. For color, different blues were used on a background of color 240 (see figure 2). Contrast was calculated at $(Au'^2 + Av'^2)^{1/2}$, where Au' and Av' indicate the differences between the u' and v' values for the two colors. This resulted in contrast values between 0.026 and 0.102.

4.1.2 *Procedure.* The basic magnitude-estimation procedure from experiment 2 was used. The observers gave magnitude estimates for a series of stimuli differing in contrast, with a standard stimulus (assigned value of 20) of intermediate contrast (which was not used in the reported results). Each series of contrasts (luminance and color) was presented ten times in different random orders. In a second part, we measured the contrast threshold for the correct identification of the location of the spot (to the left or the right of the bar). A two-alternative forced-choice response was required. Ten luminance-contrast and ten color-contrast stimuli below and above the expected thresholds were presented in separate sessions twenty times each in random order. From the frequency-of-seeing functions, we calculated the 75% threshold values by using a least-squares procedure.

4.1.3 *Subjects.* The same four observers as in the first two experiments also participated here.

4.2 *Results and discussion*

Results for the magnitude-estimation procedure are given in figure 7. In the case of luminance (figure 7a), the magnitude of the motion-induction effect did not change for two of the four observers over a range of luminance contrasts from 0.1 to 0.37. For another observer, magnitude changed somewhat (from 22 to 32) over the same range. The fourth observer showed a steeper increase, from 33 to 47 over a range from 0.15 to 0.37. For all observers, motion-induction magnitude changed much more rapidly for contrasts below 0.1 (or below 0.15 for observer MA) and levelled off toward higher contrasts. We concluded from this that increasing the contrast above about 0.1 would, at least for some observers, affect the strength of motion induction only marginally. For contrast values below 0.1 (or 0.15 for observer MA), however, the estimated strength of motion induction declined more and more rapidly for all observers. For low contrasts, therefore, the strength of the motion-induction effect depended strongly on luminance contrast.

In the case of color (figure 7b), the magnitude of the motion-induction effect did not change much (from about 20 to about 25) for three of the four observers over a range of color contrasts from 0.05 to 0.1. For observer MA, the effect of contrast was more pronounced (from about 20 to about 40 over the same range). For all observers, motion-induction magnitude declined much more rapidly for contrasts below about 0.04 and levelled off toward higher contrasts. From this we concluded that for higher color contrasts, the strength of the motion-induction effect did not vary much with contrast. For color contrast values below 0.04, however, the estimated strength of motion induction declined more and more rapidly for all observers. For low contrasts, therefore, the strength of the motion-induction effect depended strongly on color contrast.

The range of thresholds for the detection of the position of the spot obtained for the four observers is indicated by the hatched area in each graph. Comparing the results for luminance and color, we note that, for luminance, the vividness or strength of motion became very small only when the detection threshold region was reached (figure 7a), while for color the illusory-motion sensation disappeared well before the detection threshold for the position of the spot (figure 7b). We interpret this outcome in the following way. As long as the luminance or color contrast is high enough for the stimuli to be easily visible (visibility here was defined as a perceived luminance or color difference with the background), motion will be induced into the bar, and its

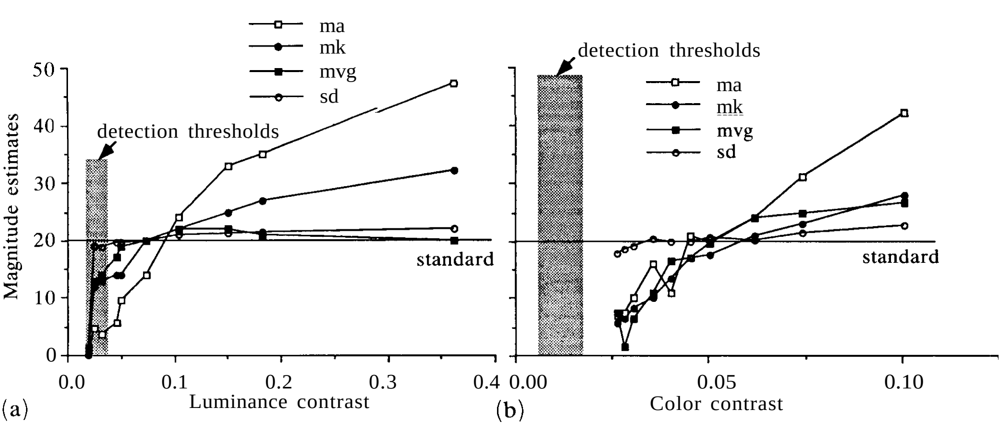


Figure 7. Results of the contrast experiments measuring the strength of the motion induction effect for (a) luminance and (b) color. Magnitude estimates are plotted as a function of contrast. The standard was set at a value of 20. The shaded areas indicate the ranges of detection thresholds for the position of the spot.

strength will be dependent on contrast only in the lower range. Only when the stimuli become almost invisible (ie near detection threshold) will performance decline. As color contrast was reduced, the impression of motion, however, seemed to disappear before the detectability of the spots.

5 General discussion

In this study, we described experiments designed to test whether the motion-induction effect was dependent on the presence of luminance contrast between the background on the one hand and the spot and bar stimuli on the other. Therefore, the stimuli used differed from the background with respect to various other attributes, such as color, texture, stereodepth, and motion, as well as luminance. No luminance contrast was present in any condition other than luminance, yet motion induction occurred just as readily as with luminance contrast, while the perceived strength of the illusory motion depended to some extent on the particular attribute(s) used to define the stimuli with respect to the background. After showing that the motion-induction effect was present for all attribute combinations, we used a magnitude-estimation technique to assess the varying strength of the effect for the various attribute combinations; this was strongest for those containing luminance and/or color as defining attributes. We also determined the influence of the amount of luminance and color contrast on the strength of the effect and found that these variables affected motion induction most at very low contrast levels close to detection threshold.

Since, at least for luminance-defined stimuli, the motion-induction effect is similar to the above-mentioned polarized gamma movement (Kanizsa 1951), we need to look at the relationship between the two. It is clear that both of them are examples of illusory motions.

5.1 *Relationship between polarized gamma movement and motion induction*

It has been known for a long time that the perceptual effect of the presentation of a visual stimulus is not immediate or simultaneous across its full extent, even when the physical stimulus is presented all at once. One result of this was described by Kenkel (1913) as gamma movement, the apparent expansion of a stimulus that is suddenly turned on. This expansion occurred from the center of the stimulus outward to its edges. Bartley (1941) attributed this phenomenon to an intensity difference between the center and the edges, due to the smudging of the edges by the optics of the eye. Combined with the fact that more intense stimuli are processed faster, this would lead to the observed expansion of gamma movement.

Kanizsa (1951, 1979) found that gamma movement can be influenced (polarized) by other nearby stimuli in the visual field, so that movement in one particular direction will be observed. In this setup, an additional stimulus was presented permanently, and a bar was then turned on near this stimulus. The bar seemed to be expanding away from the permanent stimulus. This is similar to the present motion-induction setup, where a stimulus spot is first presented and then followed after a short delay by the bar. Again, the perceived movement is within the bar, away from the other stimulus. The main difference then lies in the time between the onsets of the two stimuli. While the SOA is brief in motion induction (45 to 300 ms), it can be considered to be very long (or even infinite, ie minutes or longer) in the case of polarized gamma movement.

We compared the two effects. In one experiment, a dark square (similar in size to the one used in the experiments reported here) was glued to the screen, ie it was present permanently. In another experiment, a dark spot was presented with varying SOA, from 150 ms to 9 **s.** In each case, a dark bar followed. Results showed that motion was present within the bar in all cases, but that it was weakest for the longest

SOA and the permanent stimulus, and was strongest for short SOAs. This can be clearly demonstrated by pitting the two conditions against each other. One spot is presented on one side of the bar location, followed by another spot after, for example, 6 s on the other side of the bar location, and both are followed by the bar between them after another 150 ms. Polarized gamma movement thus should be perceived in one direction (away from the first spot), and motion induction in the opposite direction (away from the second spot). Invariably, motion was seen away from the second spot, completely overriding the gamma movement. The observation here is similar to more formal ones that we have described elsewhere under the term of 'split attention' (Faubert and von Grünau 1992). These experiments showed that two simultaneous spots on either end of the bar produced the perception of a collision of two motions from each end in the center of the bar. Moreover, the collision point could be shifted toward one end of the bar by delaying the presentation of the spot near the other end. The longer the time delay between the two spots, the more the collision point was lateralized.

We conclude from this that polarized gamma movement and motion induction may be aspects of the same phenomenon, but that motion induction produces a much stronger effect. This difference may be due solely to the transient stimulation that occurs when the spot is turned on. The longer the SOA, the more this transient will have decayed, and the weaker the motion-induction effect. In polarized gamma movement, there is no transient from the spot, yet there is a residual effect due to the simple presence of the spot. It seems that the presence and especially the on-transient or off-transient of the spot have an effect on the speed of processing of the bar, which may be understood in terms of attentional priming, discussed in the next section.

5.2 *Attentional priming*

Attentional priming may be defined as the preparatory effect that the spot has on the perception of the bar. Its mere presence, and especially its sudden appearance [or disappearance, as described by Hikosaka et al (1991)] may attract some form of attentional resources to that part of the visual field. Miyauchi et al (1992) have measured the spatial and temporal extent of this attentional field for luminance stimuli. The result of this attentional field next to one end of the bar is presumably that this end is processed faster, and thus the bar seems to be painted onto the screen from one end to the other. In different tasks it has been shown that attention can have this kind of a priming effect; Stelmach et al (1991, 1994) described experiments in which the apparent direction of stroboscopic motion was altered by directing attention at one or the other of the flashed stimuli; Miyauchi et al (1991) demonstrated that detection was faster for a cued than for an uncued line.

If one accepts this description of the motion-induction effect as an attentional phenomenon, this has implications for explanations advanced to account for gamma movement and polarized gamma movement. These were originally described by the Gestalt psychologists as the perceptual consequences of the setting up of the physiological field resulting from the stimulus presentation (eg Koffka 1935). Thus intensity factors played an important role. In our present experiments we have shown that, for higher contrasts at least, motion induction does not depend very crucially on the amount of luminance or color contrast with respect to the background, and that it starts to decay in strength only for lower contrasts and especially when the stimuli become less visible near the detection threshold. It also is not important whether the stimuli are defined by luminance or by color at equiluminance. Generally, we have shown that the phenomenon is not limited to the intensity domain, be it luminance or color. It occurred just as readily when stimuli were defined by attributes such as texture, stereodepth, or motion, without the presence of any differential luminance or color contrast. This showed that motion induction occurs for areas consisting of random-dot noise, at the same or different depth levels, with or without motion. If motion induction and polarized gamma movement are indeed aspects of the same phenomenon, one should expect polarized gamma movement to show similar insensitivities to intensity variables as described above for motion induction.

5.3 *Intraattribute and interattribute priming*

We have shown in the present experiments that the attentional-priming effect functions within as well as between the various attribute channels. Thus, the inducing stimulus can be defined in any of the tested attribute channels and will show its effect on the bar, also defined in any of the tested attribute channels. These results imply that an attentional field can be set up within any attribute channel and can influence the processing of a stimulus in any other attribute channel, albeit not to the same degree for all channels. This would suggest that we are dealing with a fairly high-level phenomenon that operates at a level at which stimulus information gathered in any of the parallel attribute channels is available. It also means that it can still affect the formation of the percept of a stimulus that is presented subsequently, sometimes after rather long delays.

We used two methods to assess the effect of motion induction for the different attribute combinations. First, we measured simply the occurrence of a directional motion in the bar stimulus, whereby observers were allowed to use a "no motion" alternative, as well as the two directional alternatives. This method is subjective inasmuch as it does not use a forced-choice approach, and subjects could have adopted various strategies of responding unrelated to their perceptions. The responses of all four observers (and those of many others who were tested informally) agreed among themselves and also with the elicited and spontaneous verbal accounts. The basic results of this approach were confirmed when a second method was used actually to estimate the strength of the perceived illusory motions. Estimates were given for all attribute combinations, ie illusory motion was seen in all cases; the strength of the effect, however, depended on the particular combination of attributes.

The inherent difficulty of comparing the strength of effects across different attributes was mentioned above. No attempts were made to equalize the stimuli across attributes, but all were far above threshold. In the contrast experiments (experiment 3), it was shown for luminance and color that the motion-induction effect disappears only when the stimuli are close to detection threshold. Away from threshold, at higher contrast levels over a limited range, the estimated magnitude of the effect did not vary very much with contrast for most of the observers. It is therefore tempting to account for the differences in the strength of motion induction observed for the various attributes not in terms of differences in effective contrast of the stimuli, but rather as indicating the existence of actual differences of the attribute channels. Thus luminance and color stand out as being both strong inducers and carriers of the effect, while the other attributes were less effective. This conclusion, however, is only tentative and needs to be confirmed by future experiments which employ stimuli equated for effective contrast across attributes.

In the assessment of the contrast effects, it was found that performance declined near the detection threshold (experiment 3). The obtained differences between the luminance and color channels are worth noting here. Within the luminance channel, the motion threshold (as given by the disappearance of the motion-induction effect) and the detection threshold occur at the same contrast level. That is, when the position of the inducing spot can no longer be determined, the motion-induction effect also disappears. Within the color channel, always at equiluminance, the motion-induction effect disappeared before detection threshold. Though here we are not talking about 'motion slowing', the kind of behavior which we observed is in line with other observations on the qualitative differences of the color channel with respect to the mediation of motion (Cavanagh et al 1984; Ramachandran and Gregory 1978).

We tested both the effect of the spot attribute and that of the bar attribute on motion induction. Generally, both determined the vividness of the illusory motion, but did not affect the readiness with which motion occurred. More specifically, the attribute of the bar, ie the carrier channel, seemed more influential in determining the strength of the effect. Thus, when the bar was defined by luminance or color, the effects were stronger for all spot attributes than when the bar was defined by, for example, motion. The attribute of the spot also had a significant influence, even though it was less pronounced. This is to say that the priming effects of the various attributes were not equivalent. Our results also show that the fact that both spot and bar were defined by the same attribute (intraattribute conditions) often but not always resulted in the strongest effects. This is further evidence that the motion induction effect is likely to be a higher-order effect that occurs at a point where input from all the attribute channels is available.

7 Summary and conclusions

In summary, we found that the motion-induction effect occurred for all combinations of stimulus attributes that we used. We conclude that the illusory motion in this effect does not crucially depend on stimulus characteristics likely to be processed early in the system. That is to say, motion induction can be obtained with only little dependence on the kind of attribute defining the stimuli and varies only little with contrast variations in the range of higher contrasts, but is weakened significantly when luminance or color contrast levels fall below 0.1 and affect the visibility of the stimuli. Overall, this is consistent with the contention that motion induction is a high-level, attention-related effect. At the same time, however, the effect is sensitive to some of the characteristics of the low-level attribute channels that carry the information.

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