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The boogie-woogie illusion

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Abstract. A grid of vertical and horizontal lines, each composed of light and dark squares, is moved rigidly at 45° to the vertical on a gray surround. When the luminance of the background is set midway between the luminances of the light and dark squares, the squares appear to race along the lines even though they are actually 'painted' on the lines. The effect arises from the unequal apparent speeds of the lines and their textures. The light and dark squares along the lines define a first-order pattern whose apparent speed, parallel or along the line, is close to veridical. The lines themselves have no overall luminance difference from the background so that they are defined by a second-order difference. As reported elsewhere, apparent speed is reduced for second-order motion so that the motion perpendicular to the line is perceived as slower than the motion along the line even though they are physically equal. The imbalance creates the impression that the small squares are moving along the lines rather than moving rigidly with them.

1 Introduction

We describe a new illusion of visual motion, which we have named after Mondrian's well known painting *Broadway Boogie-Woogie*. This painting contains checkered strips which appear to shift around during inspection in a jazzy, unstable way. Our figure 1 contains a grid of similar lines, composed of alternating light and dark squares.

If the whole pattern is moved obliquely up to the right at 1 deg s^{-1} to 10 deg s^{-1} while the eyes fixate a stationary point (or if the eyes track an obliquely moving finger, which comes to much the same thing), a curious illusion can be seen. The small squares within each line appear to flow or race along the lines. The speeded flow 'overtakes' the motion of the lines themselves, so that, if the pattern moves up to the right, the small squares seem to race up the verticals and to the right along the horizontals. Moreover, the vertical and horizontal lines look as though they are not rigidly welded together, but instead are sliding over each other (see Anstis 1990). An animated version of the illusion can be viewed on our web page at http://www-psy.ucsd.edu/~sanstis/SATric.html and the *Perception* website: http://www.perceptionweb.com/misc/p3378/. We show that the illusion is greatest when the background luminance matches the average luminance of the light and dark squares. When the background is substantially darker (or lighter) than the mean luminance of the squares, the illusion vanishes (see right side of figure 1) and everything appears to be moving rigidly.

We measured the boogie-woogie illusion in three experiments, by varying the luminance of the gray surround or the contrast of the squares and seeing how this affected the apparent speed of the squares along the lines or the apparent speed of the lines themselves. Note that 'squares' refers to the little squares that comprise the lines, and 'background' refers to the large uniform gray area between the lines. In the first two experiments, the observers viewed a computer screen that subtended 33 deg wide × 29 deg high in a dimly lit room. Viewing distance was 57 cm. On the screen was a set of vertical

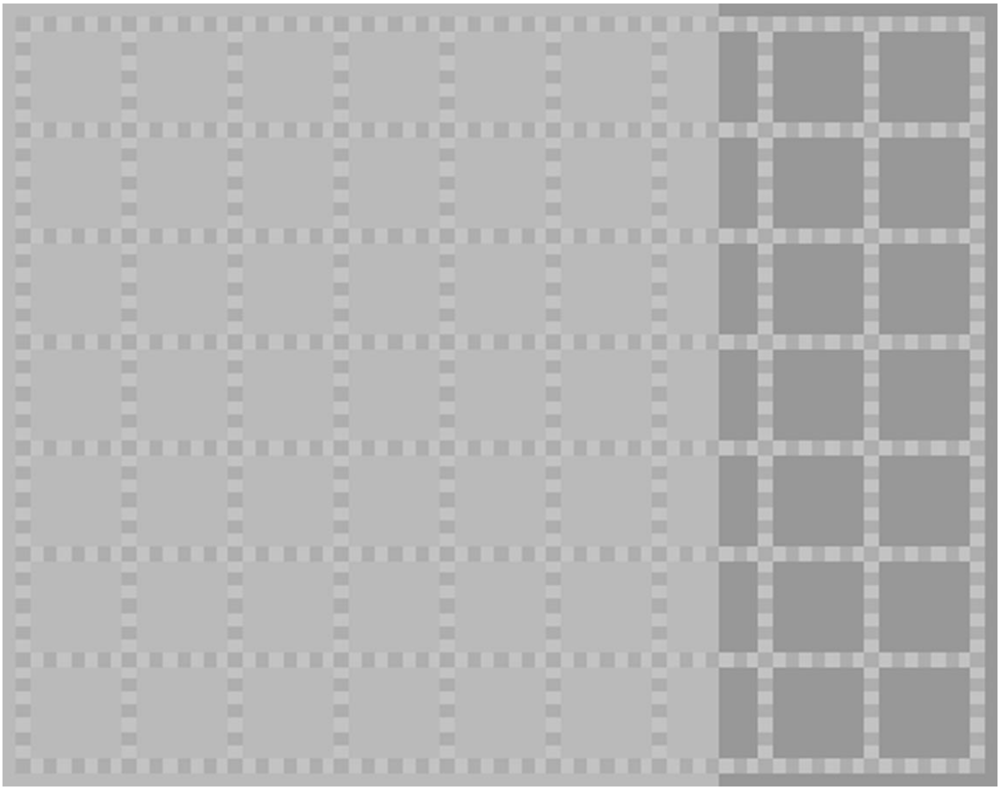

Figure 1. If this grid of checkered lines is moved in the plane of the page at 45° up and to the right, past a stationary fixated finger, the squares appear to race along the lines, upward along the verticals and to the right along the horizontals. We call this the boogie-woogie illusion, after Mondrian.

and horizontal dotted bars similar to figure 1. The bars were 0.5 deg wide and 4 deg apart, and they drifted obliquely, at 45° to the vertical, at a speed of 8 deg s^{-1} in the first experiment and 4 deg s^{-1} in the second. The squares along the lines subtended 0.5 deg $\times$ 0.5 deg. The display moved in one of four directions—up left, up right, down left, and down right—and the direction was switched on every trial to reduce adaptation effects. The monitor was calibrated for luminance linearity.

We shall show that the boogie-woogie illusion can be attributed to an overestimation of the first-order motion along the lines, plus an underestimation of the second-order motion across the lines (figure 2). Because of this difference in apparent speed, the squares appear to run along each line, overtaking the slower orthogonal lines that they cross.

2 Experiments and results

In experiment 1 the observer controlled the background luminance with a mouse, with the task of selecting the background luminance that maximized the vividness of the boogie-woogie illusion. The light and dark squares were 'painted' on the lines and moved rigidly with them despite the appearance of racing ahead along the lines. The results showed that whatever the mean luminance or contrast of the squares, the observer set the background luminance to match the mean luminance of the squares in order to maximize the illusory effect. The settings were made for dotted lines with a mean luminance of either 11.5 or 25.5 cd m^{-2}, and with their Michelson contrast at 10%, 20%, or 40%. Five observers adjusted the surround luminance to the level that

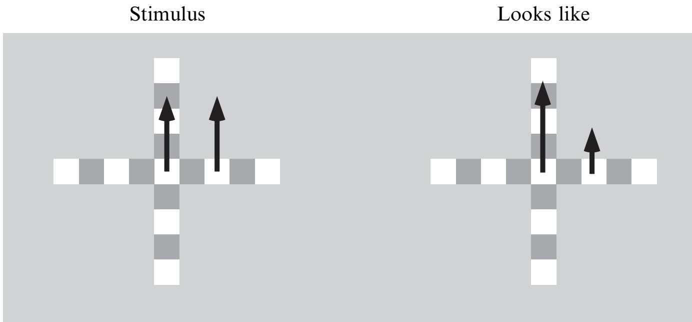

Figure 2. If the grid is moving upward, the vertical lines and the horizontal lines are both moving at the same speed as shown on the left. Our explanation of the boogie-woogie illusion is as follows. The upward motion along the vertical line is carried by the light and dark edges between the squares. These ought to activate a first-order motion response that is fairly accurate (our data show that it is even overestimated). The receptive fields of the directionally selective units that respond to these edges may extend beyond the width of each square without penalty because the stimulus is featureless to the left and right of the vertical lines. In contrast, the upward motion of the horizontal line presents a textured edge that is a poor stimulus for a first-order motion detector. A first-order detector would have to be small enough to fit within one square, either light or dark, as it passed over the receptive field. A second-order detector that would respond to a longer segment of the textured edge might be a more efficient detector of this line's motion. However, the velocity of second-order stimuli is often underestimated (Gegenfurtner and Hawken 1996). As a result the upward motion of the horizontal line will be seen as slower than that of the squares on the vertical line and these squares will appear to overtake the horizontal lines creating the boogie-woogie illusion.

gave the optimum boogie-woogie illusion, making three settings in each of the six conditions (2 mean luminances $\times$ 3 contrasts), giving 15 readings per point.

Results are shown in figure 3. The setting of the background luminance that produced the optimum illusion was typically quite close to the mean luminance of the squares (ratio of 1.0 between background luminance and mean luminance of light and dark squares as marked by the dotted horizontal line in figure 3).

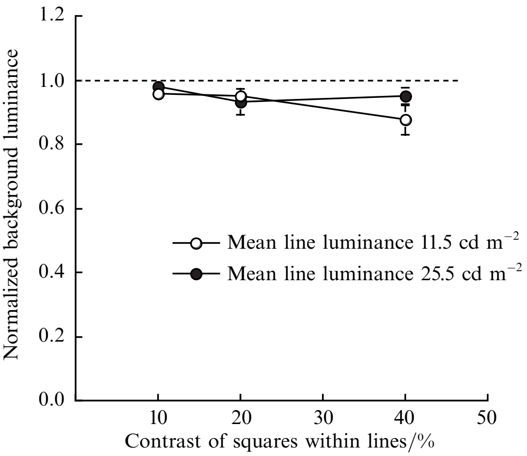

Figure 3. Settings of the background luminance that maximize the boogie-woogie illusion. The lines were presented with either 11.5 cd m^{-2} (open symbols) or 25.5 cd m^{-2} (filled symbols) mean luminance (averaging light and dark squares within the lines) and with Michelson contrasts of 10%, 20%, or 40% (between the light and dark squares). The setting for the background luminance is shown as a proportion of the mean luminance of the lines. Standard errors of the means (over five observers) are shown as vertical bars for each point when larger than the symbols ($\pm$1.0 SE).

In experiment 2, one of the authors (SA) viewed the same grid stimuli (2 mean luminances × 3 contrasts) as in experiment 1. However, the background was now set to a fixed luminance on each trial and the observer adjusted the speed of the squares along the lines to null the illusion. The squares could now move at a different speed than the lines, and once the observer had nulled the illusory motion, the lines, their squares, and the intersections, all appeared to move together rigidly. The results are shown in figure 4.

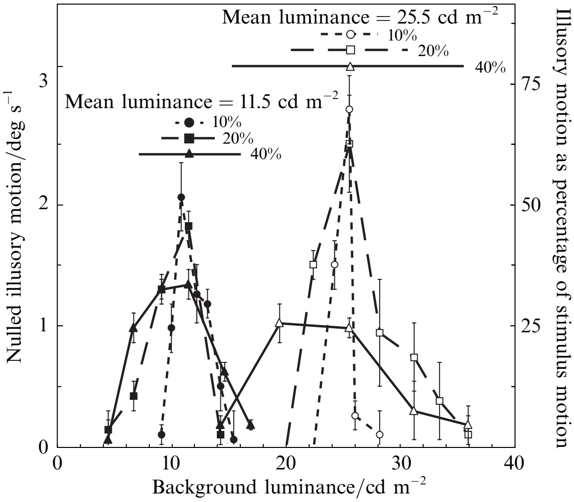

Figure 4. Motion required to null the boogie-woogie illusion as a function of background luminance for two different mean luminances and three contrasts of the lines (observer SA). Nulling motion is shown on the vertical axis, background luminance is shown on the horizontal axis. The illusion was strongest when the background luminance matched the average luminance of the lines, agreeing with the results from experiment 1. The illusion was also strongest when contrast between light and dark squares was 10% (circles), medium for 20% (squares), and weakest for contrast of 40% (triangles). The legends for the different contrasts and luminances show the span between the light and dark luminance for each stimulus as a horizontal line. Standard errors of the means are shown as vertical bars (±1.0 SE).

Figure 4 shows that the boogie-woogie illusion could readily be nulled. The velocity required to null the illusion was highest when the background luminance matched the mean luminance of the light and dark squares, and fell off steadily on either side of this maximum, approaching zero approximately when the background reached the luminance of the light or the dark square. Notice that the lower the contrast, that is the nearer together the luminances of the light and the dark squares, the narrower was the range over which the boogie-woogie illusion was found. Notice also that the narrower the curve, the higher and sharper its peak. This means that the illusion was strongest when the contrast of the squares was low.

Overall the results of experiments 1 and 2 agree in finding an optimal illusion when the average of the light and dark luminances of the squares matched the background luminance. Under these conditions, the bar can be considered to be a second-order pattern (Cavanagh and Mather 1989) having a different texture from the background but no first-order luminance difference. We believe that this is the key to the boogie-woogie illusion. We conjecture that the first-order difference between the squares along the line gives a strong motion response, leading to an accurate encoding of motion in this direction. Conversely, the second-order difference across the line gives a weak signal, leading to an underestimate of velocity perpendicular to the line (figure 2). One consequence of this imbalance is that the squares seem to race along their own lines, overtaking the slowed lines orthogonal to them.

In experiment 3 we measured separately the apparent speed of vertical and of horizontal dotted lines that moved vertically. As before, the lines had Michelson contrasts of 10%, 20%, and 40%, and their mean luminance was always equal to the background luminance. Note that the vertical lines were in first-order motion in a direction along the lines. We expected that this first-order motion would be relatively independent of contrast (Gegenfurtner and Hawken 1996). On the other hand, the horizontal lines were in second-order motion in a direction orthogonal to their orientation. We expected that the perceived speed of this second-order motion would be relatively slow at low contrast but would increase as the contrast increased (Gegenfurtner and Hawken 1996).

The lines, which were 0.25 deg wide, were spaced 2 deg apart and drifted at 2.5 deg s^{-1}. The light and dark squares were 0.25 deg $\times$ 0.25 deg in size. However, instead of a grid of horizontal and vertical lines that drifted obliquely, only the vertical or the horizontal lines were displayed on each trial, and they drifted vertically. The mean luminance of the bars and the background was 85 cd m^{-2}. Presentation was now on a 15 inch 75 Hz NEC LCD display driven by a Macintosh Titanium Powerbook. Viewing distance was 57 cm. The lines were displayed in a window 14 deg wide $\times$ 10 deg high, with its inner edge 4 deg to the left of the fixation point. A comparison window of the same size on the right of the fixation point was filled with vertically drifting white dots (160 cd m^{-2}) on a black surround. These drifting dots, also 0.25 deg $\times$ 0.25 deg, were spaced 1 deg apart on a regular square lattice. Their vertical drift rate was controlled by a mouse under the observer's control. The direction of drift of the test and comparison reversed every second to avoid motion aftereffects.

The observer's task was to set the comparison dots to drift at the same subjective speed as the checked vertical or horizontal lines. The contrast of these lines was set to 10%, 20%, or 40% in random order, and the observers, the two authors, made at least 9 successive settings at each contrast level. One observer (PC) had unlimited viewing time to make the settings. The other observer (SA) was unable to ignore the motion signals available from tracking the lines and so was given only brief (200 ms) repetitive (1 Hz) exposures to prevent tracking.

The results are shown in figure 5 for the two observers. The matched speeds on the vertical axis have been normalized to a baseline match speed set when the lines were not affected by the illusion (see below). Note that the first-order motion of the vertically drifting vertical lines was slightly overestimated (normalized matched speed

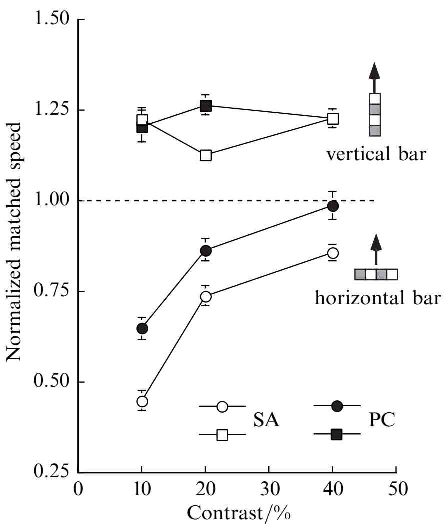

Figure 5. Normalized matched speed for vertical and horizontal textured lines, both moving vertically, as a function of line contrast. The textured lines have the same mean luminance as the background. The baseline matched speed is shown by the dotted horizontal line. Speeds above the line are overestimated and those below the line are underestimated. (Two observers, SA and PC.) Vertical bars are standard errors (± 1.0 SE).

greater than 1.0) and was more or less independent of stimulus contrast. On the other hand, the second-order motion of the vertically drifting horizontal lines was underestimated (normalized matched speed less than 1.0), and the upward sloping lines show that subjective speed increased with contrast.

The boogie-woogie illusion appears to be well accounted for by this difference in apparent speed along and across the lines. The motion of the squares along each line seems faster than the motion of the orthogonal lines of the grid, thus overtaking them. As can be seen in figure 5, the difference between the perceived speed along the line and the perceived speed of the orthogonal lines increases as the contrast drops, consistent with the observation (figure 4) that the illusion increases for lower contrasts.

Additional readings were taken with the background above or below the mean luminance of the light and dark squares of the lines. Speed matches for backgrounds very different from the mean luminance of the lines gave the baseline speed matches used to normalize the settings reported in figure 5. These additional settings also showed that the slowed speed of the vertically drifting horizontal line (second-order motion) returned to baseline as the mean luminance of the background deviated from that of the line. They showed as well that the apparent vertical speed of the squares along the vertical line was overestimated when the luminances of the line and the background matched, but dropped quickly to baseline as the background luminance deviated from the mean line luminance. An example of these readings for one observer (PC) and one contrast is shown in figure 6.

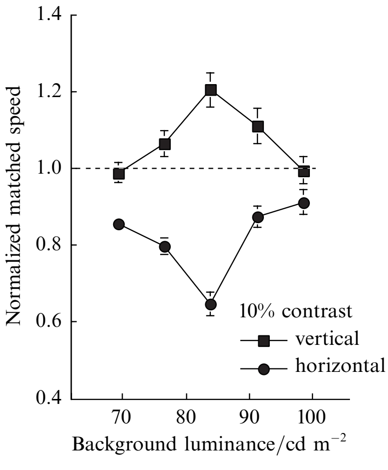

Figure 6. Normalized matched speed for vertical and horizontal textured lines, both moving vertically, as a function of background luminance for line contrast of 10% (observer PC). The baseline matched speed is shown by the dotted horizontal line. Vertical bars are standard errors (± 1.0 SE).

3 Discussion

We have demonstrated a new illusion in which the pattern elements of a compound stimulus dissociate and appear to move independently. The subjective speed of the squares along each line is faster than that of the lines they appear to cross. What is unusual in the boogie-woogie stimulus is that the imbalance in relative speed of the two components is seen directly as a loss of rigidity, with one component running over the other, rather than simply a direction shift.

In our experiment 3, we found that the apparent speed of the vertically drifting horizontal lines was underestimated. We claim that this is because they are second-order patterns (Cavanagh and Mather 1989; Chubb and Sperling 1988). Several other studies have reported slowing for second-order stimuli. In some conditions, second-order motion may not appear slowed (Ledgeway and Smith 1995, 1997); however, especially in the periphery, second-order motion can slow down substantially or actually look immobile (Pantle 1992; Zanker 1997; but see Smith et al 1994).

Gegenfurtner and Hawken (1996) measured perceived velocity as a function of contrast for various kinds of first-order and second-order moving gratings and plaids. For stimuli that did not move too quickly, perceived velocity varied with contrast. The slope of this perceived velocity versus contrast line (velocity gain) was relatively shallow for first-order gratings and plaids. The slope was much steeper for second-order gratings and plaids that were defined by color or texture, indicating that the apparent speed slowed significantly as contrast dropped. Thus, especially at low contrasts, second-order patterns appeared to move much more slowly than first-order.

We have shown that the boogie-woogie illusion is a result of the slowed perception of motion across the texture lines (second-order motion) compared to the veridical or even speeded perception of motion along the lines (first-order motion). While there have been many prior reports of speed difference for first- and second-order stimuli, we believe the boogie-woogie illusion is novel for its demonstration of these speed differences in the same direction within the same stimulus. This allows observers to experience these speed differences directly rather than by comparison across different stimuli. This illusion should therefore be a useful tool for quickly assessing other factors that might affect the two motion systems differentially.

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