Reference repulsion when judging the direction of visual motion

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Abstract. While humans are very *reliable* (ie give highly reproducible answers) when repeatedly judging the direction of a moving random-dot pattern (RDP) we find that their *accuracy* (ie the direction they so reliably report) shows systematic errors. To quantify these errors, we presented a complete set of closely spaced directions and mapped the directional misjudgments by asking subjects to compare the perceived direction of a moving RDP with the direction of a test line. The results show misjudgments of up to 9°, which are best accounted for by a tendency of the subjects to overestimate the angle between the observed motion and an internal reference direction.

A control experiment in which subjects had to judge the spatial distance between a point and a line demonstrates that these misjudgments are not confined to motion stimuli but rather seem to reflect a general tendency to overestimate the distance between a stimulus and a reference when they are close to each other.

1 Introduction

Reliable judgments of the direction of motion are important and therefore in many studies the thresholds for direction discrimination have been investigated (Tolhurst 1973; Mather and Moulden 1983; Ball and Sekuler 1982, 1987; Heeley and Buchanan-Smith 1992a, 1992b; Mullen and Boulton 1992; Wright and Gurney 1992; Gros et al 1997; Flinn and Watamaniuk 1997). There is also an extensive literature concerning measurements of orientation thresholds (eg Appelle 1972; Wenderoth and White 1979; Orban et al 1984; Heeley and Buchanan-Smith 1988, 1990, 1992a, 1992b; Buchanan-Smith and Heeley 1993) with orientation discrimination almost always found to be better for cardinal than for oblique orientations—the so-called ‘oblique effect’ (Jastrow 1892; see also Caelli et al 1983; Regan and Price 1986; Heeley and Timney 1988).

While these studies demonstrated low discrimination thresholds for orientation and direction of motion, they did not deal with the *accuracy* of perceived orientation or direction. Except for a recent study by Blake et al (1997), the only studies which have specifically examined the perceived direction of a moving pattern are those that have looked at the effect of one direction on the perceived direction of another direction when two random-dot patterns (RDPs) move transparently across each other. Marshak and Sekuler (1979) used a protractor scale to report the perceived direction of one of the motions. In similar studies by Levinson and Sekuler (1976), the moving patterns were followed by a test line of adjustable orientation, and the subject's task was to set the line parallel to the axis along which one of the test patterns appeared to drift. In the experiments of Yo and Wilson (1992), a blank screen appeared after each presentation of the transparently moving RDPs, followed by the image of a pointer. The pointer could be rotated, and the subject aligned the angle of the pointer to the perceived direction of one of the patterns. The overestimation of the angle between the two directions observed in all these studies has been termed motion repulsion and has been interpreted as an interaction between the two motions. An important implicit assumption has been that perception of each of the two directions alone is veridical. Hiris and Blake (1996) removed the need for this assumption by subtracting possible

misperceptions of the single direction from the results derived with two directions. They reported much smaller motion repulsion, presumably because of systematic misperceptions for the individual directions, although they never explicitly stated the amount of such misperception.

In the study of Blake et al (1997) such misperceptions are plotted in the context of an experiment in which the decay of directional memory with increasing memory intervals of up to 8 s has been investigated. Such misperceptions were not the main focus of the study and while the authors discuss possible systematic biases of perceived directions in the context of several hypothetical bias models they found no single, obvious pattern of errors when visually inspecting the raw data of the individual observers.

Here, using a different method we systematically tested the misjudgments of a single RDP at 36 directions between 0° and 360° . In the first experiment we presented a RDP and asked subjects to compare the perceived direction against a successively presented oriented line. Thus subjects had to momentarily hold the RDP in memory until the appearance of the line. To avoid such a memory component, in the second experiment we used a simultaneous presentation of the motion and a virtual line. In both experiments we found robust systematic misjudgments that were best explained by a tendency to overestimate small angles between a motion and a reference direction, a phenomenon we term 'reference repulsion'. In a third experiment we demonstrate that this behaviour is not confined to judgments of motion direction but also affects judgments of spatial distance.

2 Methods

The experiments were performed on an Apple Macintosh computer and a monitor with 74.5 Hz frame rate. The spatial resolution of the display was $33.3 \text{ pixels deg}^{-1}$. Our stimuli consisted of RDPs presented behind a virtual aperture 9.2 deg (6 deg in experiment 2) in diameter. Each RDP had a density of 3 black dots ($3.6 \text{ min arc in width}$) deg^{-2} . All dots moved uniformly at 4 deg s^{-1} for a stimulus duration of 1 s, with dots disappearing behind the aperture reappearing at the opposite side of the stimulus. The subjects viewed the display binocularly in a dimly lit room from a distance of 57 cm, maintained by a chin rest.

Each experiment consisted of 36 possible directions ($5^\circ, 15^\circ, 25^\circ, 35^\circ, \dots, 355^\circ$; with 0° corresponding to upward motion and 90° representing rightward motion). In an experiment, each of these 36 stimuli was presented fifteen times in random order. Most of the subjects performed each experiment three times. For each subject the final estimate of each of the 36 perceived directions was the average of the three measurements.

The same eleven subjects served in all experiments. Eight were paid volunteers naive to the research aim and three were from within the laboratory. All had normal or corrected-to-normal visual acuity.

2.1 Experiment 1

In each trial, a line with two markers was presented immediately *after* the moving dot pattern (figures 1a and 1b). In a two-alternative forced-choice (2AFC) paradigm, subjects were required to indicate whether the perceived direction was more counter-clockwise (towards the grey marker) or clockwise (towards the black marker) than the orientation of the line. The line was visible until the subjects made a decision. In a 1-up 1-down 50% staircase procedure, the line was moved towards the perceived direction of motion after each trial. So, if the subject reported a direction of motion to be clockwise from the line, the next presentation of that direction would be followed by a line oriented more clockwise and vice versa. This allowed a precise determination of the perceived direction of motion and the trial-to-trial variability allowed us to estimate the subjects' direction discrimination threshold for each direction.

Figure 1. (a) and (b) Successive presentation of moving RDP and a line. The three arrows in (a) show one direction of a set of moving dots. The black line in (b) represents the orientation of the line to be compared to the perceived direction of the moving dots. (c) Simultaneous presentation of moving RDP and two line segments. The three arrows show one direction of a set of moving dots. The two black line segments represent the orientation to be compared to the perceived direction of the moving dots. The dashed circle is just for illustration purposes and does not appear in the actual experiment.

2.2 Experiment 1b

In order to exclude aliasing effects of the pixel grid as the basis for our findings in experiment 1, we repeated experiment 1, but rotated the monitor 20° clockwise. We also attached a round aperture in front of the monitor to occlude the monitor sides and prevent subjects from seeing the orientation of the monitor.

2.3 Experiment 2

Two line segments were presented *simultaneously* with the moving dot pattern (figure 1c). The subject had to decide whether the perceived direction of motion of the RDP was more clockwise or counterclockwise than the virtual orientation formed by the line segments. The same staircase method was employed to determine the perceived direction of motion. The simultaneous presentation allowed the subject to compare the direction of the RDP directly with the orientation of the lines. With the lines not continuing through the RDP it was impossible for an observer to base her or his judgment on points actually crossing the line. The RDP and the two line segments were presented for 1 s.

3 Results

3.1 Experiment 1

Figure 2 shows the result of experiment 1 averaged across the eleven subjects. The angle between the presented and the reported direction is plotted against the presented direction of movement. Positive values represent reported directions that are further clockwise than presented directions while negative values represent reported directions that are further counterclockwise. Veridical judgments would result in a horizontal line with a y value of 0. Instead, subjects show systematic misjudgments of up to 9° alternating with zero-crossings near the diagonals and the cardinals (up, down, right, or left). This pattern of errors is easiest to describe as an overestimation of the angle between the presented direction and the nearest cardinal direction.

Figure 2. Results of experiment 1. Mean error in reported direction as a function of the direction of motion at successive presentations of a moving RDP and a line. Positive values on the ordinate indicate that the reported direction was shifted clockwise from the actual direction. Each data point is the average of measurements from eleven subjects. Vertical bars represent the standard errors. Asterisks indicate values that are significantly different from 0 ($p < 0.05$).

3.2 Experiment 1b

Because the stimuli were dots plotted on a computer monitor the special role of the cardinal and diagonal directions might have been caused by aliasing effects of the pixel grid. To rule this out we repeated experiment 1 (figure 3, thick solid curve), but with the monitor rotated clockwise by 20° . If the waveform of figure 2 is caused by the orientation of the monitor we would expect it to shift with the monitor orientation (figure 3, thick dashed curve). If the monitor orientation plays no role, the curve should remain unshifted. Our results (figure 3, thin curve) show a curve with almost the same phase as in experiment 1 and not like the expected effect of aliasing.

3.3 Experiment 2

Presenting the RDP and an orientation simultaneously, we again measured systematic misjudgments of the noncardinal directions (figure 4). In contrast to experiment 1 the misjudgments were overestimations of the angle between the presented direction and the nearest *horizontal* direction. The directions presented upward from the horizontal (270° – 90°) were judged further upward; the directions presented downward from the horizontal (90° – 270°) were judged further downward.

Figure 3. Results of experiment 1b. Mean error in reported direction as a function of motion direction at successive presentations of a moving RDP and a line. The thick, solid curve is a sine wave fitted through the data of experiment 1. The thick, dashed curve would result with a monitor rotated 20° clockwise if the waveform of the curve of experiment 1 was shifted with the monitor's orientation. The thin, solid curve shows the fit through the actual data of experiment 1b (circles) with the monitor rotated 20° clockwise. While the fitted sine wave shows a somewhat higher magnitude the phase (90.8°) is almost identical to the one from experiment 1 (89.9°) and almost exactly 20° different from the phase of the thick, dashed curve (70.8°).

Figure 4. Results of experiment 2. Mean error in judged direction as a function of the direction of motion during the *simultaneous* presentations of a moving RDP and a line. Conventions as in figure 2.

3.4 Experiment 3

To test if the pattern of directional misjudgments we found in the previous experiments is a general phenomenon we designed a similar experiment in a non-motion domain. Subjects were asked to perform a spatial separation judgment when presented with a vertical line and a nearby circle. The possible distances between the line and the centre of the circle (0.6 deg diameter) were 0.6, 0.9, 1.2, 1.5, and 1.8 deg. The line was

visible throughout each trial. A 133 ms presentation of one of the possible circles was first followed by a mask (1 s) and then a point (figure 5a). The subject had to decide if the centre of the circle had been to the left or to the right of the point. As in the direction-judgment experiments above, the point was moved towards the perceived position of the centre of the circle after each trial by a staircase procedure. The mask consisted of three different groups of overlapping circles appearing successively in random order so that every combination was visible for 333 ms. None of the five possible test circles was part of the masks. All masks appeared at the same place on the screen independently of the presented test circle.

Figure 5. (a) Experiment 3: presentation of a circle and a nearby line as a reference (for 133 ms), followed by a mask (1 s) and then a single point; the line was visible throughout the trial. (b) Results of experiment 3: average error (min arc) in reporting the distance of a circle from a vertical line as a function of the distance of the circle from the line (min arc). Positive values on the ordinate indicate that judged distances were overestimated. Vertical bars represent the standard errors of the mean across seven subjects. Asterisks indicate values that are significantly different from 0 ($p < 0.05$). The oblique line represents the hypothetical result, if the subjects had chosen to use the centre of the group of circles in the mask for his/her answer (see text for details).

Subjects overestimated the distance of the circle from the line for small circle–line separations. In figure 5b this bias is plotted as a function of the actual distance.

It is theoretically possible that observers, although instructed to judge the centre of the target circle relative to the spot, tended to judge the centre of the group of circles in the mask because of the brief target duration and the long mask duration. The oblique line in figure 5b represents the result of such a behaviour by the subjects. Clearly the data are much better accounted for by a repulsion effect from the true position of the circle.

4 Discussion

Our results demonstrate systematic misjudgments of the direction of moving random-dot patterns. These misjudgments cannot be accounted for by monitor aliasing effects (experiment 1b) and are instead best explained by a perceptual repulsion (ie overestimation of the angle) of the presented direction from a nearby reference direction. We call this phenomenon reference repulsion. While different experimental paradigms can influence which directions will serve as reference directions, they still lead to reference repulsion.

In the case of *successive* presentations of a moving RDP and a line (experiment 1), the data are best explained by a repulsion of motion direction from the nearest of the four cardinal directions (upward, downward, leftward, and rightward motion). Therefore, when the directional misjudgment is expressed as a repulsion from the nearest cardinal direction, most values are positive (figure 6b).

With *simultaneous* presentations of a moving RDP and an illusory line (experiment 2), subjects seem to use only the horizontal directions (leftward and rightward motion) as a reference. Therefore, when the data are plotted as deviations from the nearest of the four cardinal directions, both attraction and repulsion seem to happen (figure 6d), whereas measuring the errors as a repulsion from the nearest *horizontal* direction results in repulsion throughout (figure 6c).

Figure 6. Plots of the amount of repulsion relative to the nearest horizontal direction (a) and (c) and to the nearest of the four cardinal directions (b) and (d). Data of the upper graphs are from experiment 1; data of the lower graphs are from experiment 2. Positive values indicate repulsion; negative values indicate attraction in relation to the respective cardinal direction.

Blake et al (1997) also found biases of perceived directions of RDPs. Their study focused on the effect of memory duration on the accuracy of remembered directions, but they also discussed possible biases. They visually inspected the raw data from their individual observers and reported that they did not find a single, obvious pattern of errors across observers. While some of the observers clearly showed a pattern very similar to ours, the effect seems to be hidden in a lot of trial-to-trial variability. Given the differences in the experimental paradigm (they used a point-and-click technique where the observer used the computer mouse to specify the perceived direction; they did not average within or across observers; they used fewer observers) it seems likely that they tapped into the same mechanism but that it was obscured by noise.

4.1 No correlation between the magnitude of the direction discrimination threshold and the amount of repulsion for a given direction, but evidence for an oblique effect

We were wondering if there was a correlation between the magnitude of repulsion and the magnitude of the direction discrimination threshold for a given direction, ie if a higher threshold leads to stronger repulsion. We determined the discrimination thresholds for the various presented directions by fitting a probit through the data from the fifteen presentations of a given direction. We found no correlation (correlation coefficient < 0.15) between the amount of repulsion at a given direction and the corresponding direction discrimination threshold (ie the steepness of the probit fit). Thresholds were not higher for stimuli that caused pronounced misjudgments compared to stimuli that caused small or no misjudgments.

We did, however, find a correlation between directions and thresholds. Direction thresholds increased with increasing angles to the cardinal directions. This is an oblique effect for direction of motion (Coletta et al 1993; Gros et al 1997; Flinn and Watamaniuk 1997). These raised direction discrimination thresholds (but not of the misjudgments) at oblique directions might be due to an uncertainty in the orientation of the test lines because of the well-known oblique effect for orientation (eg Appelle 1972).

4.2 Reference repulsion is not confined to judgments of motion direction

In experiments 1 and 2 we found a perceptual repulsion of a motion direction from internal reference directions—the cardinal directions. Experiment 3 demonstrated a similar repulsion phenomenon in the domain of spatial separation by showing that the distance of an object from a reference line is overestimated for small object-to-line distances. This strongly suggests that reference repulsion is a general phenomenon, not confined to judgments of motion direction.

This is in agreement with Huttenlocher et al (1991), who also found a bias in the non-motion domain when asking subjects to report the location of a dot in a circle.

Our results suggest that subjects do not encode all sensory parameters (like direction of motion or spatial position) in absolute terms, but instead represent it in relation to the closest reference (eg a cardinal direction or a nearby landmark, like the stationary line in experiment 3). Additionally, in what seems to be designed to enhance differences, subjects overestimate the distance of the parameter to the reference, creating what we call reference repulsion. How many references are available and which ones are used seems to depend on the experimental design. Our experiments suggest that for judging the direction of motion subjects have at least four references (the four cardinal directions) at their disposal, but will make use of all four only when the task is demanding, such as when there is a time delay between the presentation of the motion and the judgment line (experiment 1).

4.3 Relevance for other studies

While many studies have looked at the discriminability of directions, only a few have looked at the perceived direction in absolute terms. Besides the recent study of Blake et al (1997), notable exceptions are the experiments measuring the amount of motion repulsion (eg Levinson and Sekuler 1976; Marshak and Sekuler 1979; Mather and Moulden 1980; Hiris and Blake 1996), where subjects had to judge the direction of one of two RDPs moving transparently across each other at an acute angle. Misjudgments of up to 20° have been reported in these studies. Our demonstration of reference repulsion suggests that the misperception of the direction of the RDP that had to be judged is not solely due to the presence of a second RDP. Instead, in pilot studies we found that the effect of reference repulsion accounts for about one-third of the amount previously reported as motion repulsion. This correction of the magnitude of motion repulsion has important consequences, since models of direction selectivity

can more easily account for the reduced motion repulsion than for the much larger amount reported without correction for reference repulsion.

Our finding of reference repulsion might also explain why Hiris and Blake (1996) found only about 10° of motion repulsion even though they used a design very similar to the one employed by Marshak and Sekuler (1979), who reported a motion repulsion of about 20°. The biggest difference was that Hiris and Blake measured repulsion not against the true direction of the presented motion but against the perceived direction of a single moving pattern. Thus they implicitly removed the contribution of reference repulsion from their measurements.

4.4 *Is reference repulsion a 'sensory' or a 'cognitive' phenomenon?*

Our data do not allow us to decide if the misjudgments we observe are already present at an early level of visual information processing, such as direction-selective cells in striate or extrastriate visual cortex or if the misjudgment only occurs at a higher cognitive stage when encoding, memorising, and reporting the perceived direction. Huttenlocher et al (1991) propose a very interesting model for the latter possibility. Assuming truncation at category boundaries (like the cardinal directions) and weighting with a central, prototypical category value (such as oblique directions of motion), they show that, even when the sensory signal is unbiased, such a model will introduce a bias, but nevertheless may improve overall accuracy by decreasing the variability of reports. On the other hand, there are types of perceptual misjudgments, such as the overestimation of contrast differences at contrast boundaries (the so-called Mach band) that are most likely caused by the sensory properties of the neurons encoding these stimuli and not by higher cognitive processes. More research and most likely physiological measurements will be needed to answer this question.

In conclusion, we have demonstrated systematic shifts of judged directions of moving RDPs, an effect we term reference repulsion. Given the generality of this phenomenon, it has great experimental relevance and should be considered as a contributing factor in many studies that aim to determine absolute values of perceived features by comparing them against similar reference features.

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