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Reflexive gaze orienting induces the line-motion illusion

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Abstract

When a static line is presented near a brief cue, participants report motion within the line from the cued end towards the uncued end. Attention may mediate this effect by speeding the processing of the attended end of the line; however, apparent motion mechanisms between the cue and the line may also contribute. This study uses a new type of attentional cue, reflexive gaze orienting (RGO), which recruits attention automatically but uses a cue presented remotely from the line. Thus, RGO rules out motion mechanisms that might be recruited by a cue appearing in the vicinity of the line, and allows one to evaluate the contribution of attention per se to the illusion. In three experiments, RGO induced the line-motion illusion, establishing attention as a source of the illusion. Although attention may accelerate processing at the attended location, alternative mechanisms by which attention could cause the line-motion illusion are considered.

Keywords: Motion; Attention; Line motion; Reflexive gaze orienting

1. Introduction

In the last few decades, evidence has been mounting for the role of attention in perception. It is now well documented that attention enhances both the sensory properties of visual stimuli and our ability to discriminate among visual stimuli. For example, orientation thresholds for sine-wave gratings are lower when the stimuli are attended than when they are unattended (Lee, Koch, & Braun, 1997). Thus, visual attention enhances our perceptual sensitivity, and recent research indicates that its effects can be observed at the earliest stages of cortical processing (Posner & Gilbert, 1999; Rees, Backus, & Heeger, 2000). A more contentious issue concerns the influence of visual attention upon the speed of processing, and in particular whether attention accelerates the transmission of information at the earliest stages of cortical processing.

It is well known that a cue stimulus can lead to faster detection or identification of a probe stimulus (Posner, 1980). The source of this effect, however, is a subject of contention. Whereas it could be the case that visual attention accelerates the processing of attended stimuli as early as the primary and secondary visual cortices (Grunau, Racette, & Kwas, 1996; Grunau, Saikali, & Faubert, 1995; Hikosaka, Miyauchi, & Shimojo, 1993a; Schmidt & Klein, 1997; Stelmach, Herdman, & McNeil, 1994), alternative explanations are also possible. More recently, the line-motion illusion has been taken as support of the view that visual attention increases the speed of processing at the earliest stages of visual processing. In the classical version of this illusion, a brief cue followed by a static line leads to the perception of the line being drawn away from the cue (Hikosaka et al., 1993a,b,c; Steinman, Steinman, & Lehmkuhle, 1995). Hikosaka et al. (1993a), who first reported that effect, proposed that visual attention, captured by the brief cue, accelerates the processing of visual information around the cue, leading to a percept of motion from the attended side of the line to the unattended side of the line. In this view, visual attention affects the timing of the inputs from early visual areas to motion detectors in MT/MST. However, to this day, there is much debate about the source of this illusion. Although it could be due to attention accelerating early visual processing, it could also be caused by sensory phenomena, such as sensory facilitation, around the cue (Schmidt & Klein, 1997), and/or apparent motion between the cue and the line. Indeed, line-motion stimuli are quite similar to those producing apparent motion (see Downing &

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Treisman (1997) for a discussion). As in typical apparent motion displays, two stimuli are presented successively in slightly different locations. Accordingly, a number of studies have established that apparent motion can contribute to the line-motion illusion (Downing & Treisman, 1997; Grunau, Dube, & Kwas, 1996; Grunau & Faubert, 1994; Kawahara, Yokosawa, Nishida, & Sato, 1996).

The goal of the experiments presented below is to prevent contributions from sensory facilitation and apparent motion to determine the extent to which attention alone can lead to the line-motion illusion. Although the role of attention in the illusion has been extensively tested in previous research, the arguments and empirical findings used to establish attention as the source of the illusion have come under criticism (Downing & Treisman, 1997; Klein & Christie, 1996). In particular, the illusion has been tested almost exclusively with displays in which the line appeared near a sensory cue (be it by a luminance patch, color patch or even a sound at a nearby location) (Grunau & Faubert, 1994; Shimojo, Miyauchi, & Hikosaka, 1997). These experiments allow for confounds between attention and lower level mechanisms such as sensory facilitation and apparent motion (Schmidt & Klein, 1997). In the latter case, a link may become established between the cue and the line allowing for a bias in the choice of objects to be bound across spatial and temporal intervals. To avoid this confound, the experiments described in this paper used reflexive gaze orienting (RGO) to attract attention to a specific location (see Fig. 1). RGO is the finding that observers' visual attention follows the direction of gaze of cartoon faces or eyes (Friesen & Kingstone, 1998; Langton & Bruce, 1999). This form of attentional orienting was chosen because it uses a cue presented in the center of the display to direct attention to a given peripheral location, thereby permitting the rejection of sensory facilitation or aparent motion explanations of the illusion, if observed. Note that endogenous attention, oriented for example by a central arrow cue, has the same property; however, unlike endogenous attention, RGO is automatic and not under volitional control. Indeed, facilitation of processing in the direction of gaze is observed even when participants know that the direction of gaze is four times less likely to correspond to the target location (Driver et al., 1999). This point is important since participants do not directly benefit from paying attention at one location or another during line-motion illusion experiments, and so may ignore the attentional manipulation when possible. As noted by Schmidt (2000), this may explain the mixed results obtained when using endogenous attention in previous studies of the line-motion illusion (Downing & Treisman, 1997; Hikosaka, Miyauchi, & Shimojo, 1993c; Klein & Christie, 1996).

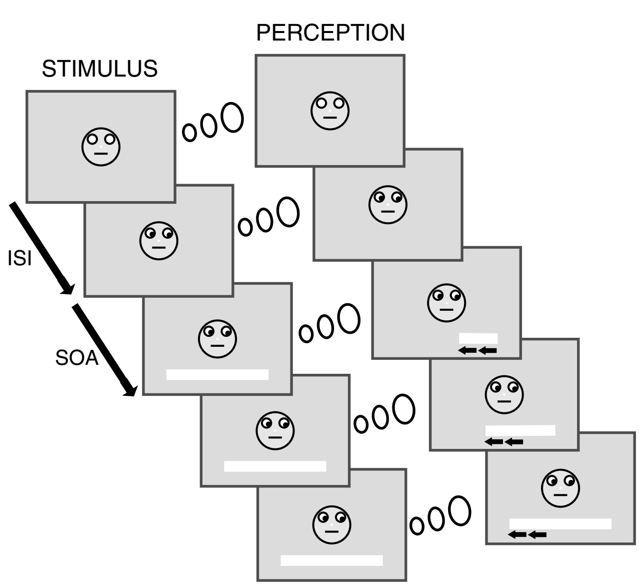

Fig. 1. Example of the sequence of stimuli used in a trial in which the line was presented in one frame, i.e. static. The associated percept of illusory motion is depicted on the right. Subjects report seeing motion in the line travelling away from the attended end, toward the unattended end.

To summarize, our goal is to determine whether RGO can produce the line-motion illusion. Because RGO involves the presentation of transient cues near fixation, and not near the line itself, it allows one to rule out sensory facilitation and apparent motion as sources of the line-motion illusion. Thus, observing the line-motion illusion using RGO would unambiguously establish that attentional factors can lead to categorical changes in perception such as the modification of the perceived direction of motion.

2. Experiment 1

The goal of Experiment 1 is to determine whether RGO can lead to the line-motion illusion. As in the classical line-motion illusion paradigm, participants were asked to focus on a fixation point and to categorize the direction of motion (leftward versus rightward) of a line presented in their peripheral visual field. Unlike in previous studies, the fixation point was the nose of a cartoon face, as illustrated in Fig. 1. After a variable ISI, pupils, which served as attentional cues, appeared looking either straight-ahead, to the lower left or to the lower right. Three hundred milliseconds later, a line was displayed across the lower visual field. As in a number of previous studies of the line-motion illusion (Kirschfeld & Kammer, 2000; Miyauchi, Shimojo, & Hikosaka, 1991; Steinman et al., 1995), the line could either appear at once or be drawn to the left or to the right with different velocities. Participants were asked to decide if they saw rightward or leftward motion in the line. This allowed us to map the perceived motion direction as a function of the velocity of the line. When the pupils looked straight-ahead, we expected veridical perception, such that participants should be maximally uncertain about the direction of motion when the line is static. If attention induces motion away from the attended location, we predicted that when the eyes looked to the right, participants would tend to perceive motion away from the right. Thus, in that case, participants would be maximally uncertain about the direction of motion when some rightward motion was added to the line to cancel the motion induced by attention. By the same logic, the opposite bias was predicted when attention was directed to the left (see Fig. 2).

Additionally, if attention is responsible for the change in the perceived direction of motion, the strength of the line-motion illusion should be sensitive to the time it takes attention to be oriented. The existing literature on RGO indicates that the effects of this form of attention emerge around 100 ms after the cue, appear most robust around 300 ms, and decrease thereafter (Driver et al., 1999; Langton & Bruce, 1999). Thus, the illusion should be absent as long as attention has not had time to switch to the cued location, increase in strength as attention gets allocated to the cued location, and then eventually decrease. This hypothesis is tested in Experiment 1 by comparing the strength of the illusion in conditions in which the cue precedes the line by 300 ms (maximal attention), the cue and the line are simultaneous (no attention yet), or the cue precedes the line by 1000 ms (declining attention).

2.1. Participants

Ten observers participated in this experiment, including the three authors, six naïve participants, who received monetary compensation, and one lab member. The mean age of the participants was 26 years (range: 19–34 years), and three participants were female.

2.2. Methods

Stimuli: A cartoon face, 6.4° of visual angle in diameter, was presented with its nose in the center of the screen. At first, the face contained white eyes, 1.6° in diameter, with no pupils, and was displayed for a variable ISI ranging from 500 to 1500 ms. Then, black pupils, 0.48° in diameter, which served as the attentional cue, were presented, looking either straight-ahead (straight-ahead gaze condition), to the lower right (right-gaze condition) or to the lower left (left-gaze condition). Finally, a horizontal line, 30.8° long and 0.32° wide was presented in the lower visual field. The line was centered with respect to the nose; the shortest distance between the pupils and the line was 7.7°, and 16.6° between the pupil and the left and right extremities of the line. Thus, the visual transient induced by pupils was at least 16° away from either line extremity. This configuration rules out any explanation of the line-motion illusion in terms of sensory facilitation or apparent motion. Indeed, sensory facilitation is not expected over such a spatial distance, and apparent motion between the transient of the cue and that of the line would predict downward motion or possibly oblique motion, but not a purely left-right gradient as predicted by the line-motion illusion. Three main factors were manipulated in this experiment: the direction of attention, which could take three values (straight-ahead gaze, left gaze—gaze to the lower left, and right gaze—gaze to the lower right), the timing between the cue and the line (stimulus onset asynchronies (SOA) of 0, 300 and 1000 ms) and the velocity of the line. Seven different velocities were used. The line could be drawn at once in one video frame or in parts in 3, 5, or 7 frames, starting either from the left or from the right. We will thereafter plot the data as a function of the delay between the onset time of the first line segment drawn and the onset time of the last line segment drawn. This time delay varied from 0 ms (1 video frame) to 37.5 ms (7 frames). When the line was drawn in 3, 5 or 7 frames, 1/3, 1/5 or 1/7 of the line was drawn in each video frame, corresponding to phi-motion velocities of 1643, 986 and 704 deg/s. The line presented as one segment at one time corresponds to an infinite velocity. Although these velocities are high compared to those used in previous studies, the mechanism that cancels the perceived velocity in the line does not seem to depend on the length of the line (Grunau, Racette, et al., 1996). Accordingly, we have observed in our lab that the cancellation delay, in terms of the number of frames necessary to draw the line, does not vary substantially across lines of different lengths.

Apparatus: The experiment was performed using a MacIntosh G3 computer (Apple Computer Inc., Cupertino, CA) running a program to present stimuli and collect the data using the Matlab computer language (The Math Works Inc., Natick, MA) and the Psychophysical Toolbox routines (Brainard, 1997; Pelli, 1997). The stimuli were displayed on a ViewSonic P817 21 in. monitor (ViewSonic Inc., Walnut, CA) driven at 160 Hz by an MP850 video card (Village Tronic Computer, Sarstedt, Germany).

Procedure: Participants sat with their chins comfortably set in a chin rest, 35.5 cm away from the screen. The chin rest's height was adapted to each participant so that his/her straight-ahead gaze was leveled with the fixation point. The psychometric curve for each direction of attention was sampled by testing seven different velocities with 20 trials per velocity for each of the three attention conditions and the three SOA conditions, for a total of 1260 trials. All conditions were randomly intermixed. The trials followed each other with a variable interval ranging from 500 to 1500 ms. After every block of

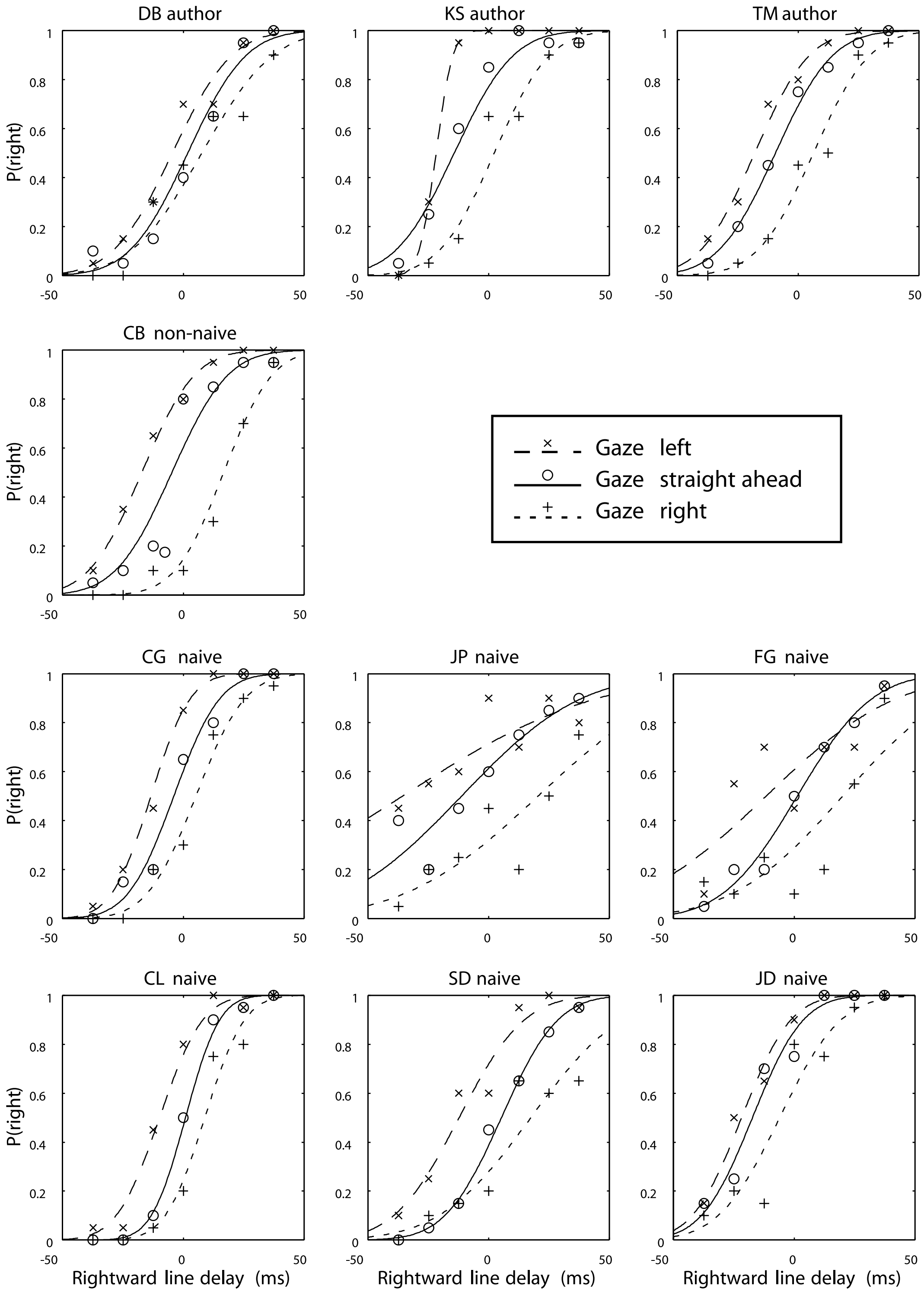

Fig. 2. Data from the nine participants included in Experiment 1. The fraction of perceived rightward motion is plotted on the *y*-axis as a function of the line motion added to the display. The latter is plotted as the time delay necessary to draw the line in milliseconds; positive numbers mean that the line was drawn from left to right (rightward motion added), negative numbers correspond to cases where the line was drawn from right to left (leftward motion added). Data points are indicated along with their best fitting cumulative normal function. As can be seen, the psychophysical curves shift as a function of the location of attention. A rightward shift occurs when subjects attended to the right as compared to when attending to a neutral position (gaze straight-ahead). This indicates that, when attention is directed to the right, subjects perceive motion away from the right and rightward motion must be added to the line so that participants are maximally uncertain of the motion direction. Similarly, a leftward shift occurs when subjects attended to the left.

50 trials, the program paused, allowing participants to rest. The length of the pause was self-paced; on average, the experiment lasted about 90 min.

A two-alternative forced choice (2AFC) task was used in which participants determined whether rightward or leftward motion was present in the display. Participants responded on the keyboard by pressing the left-arrow key for leftward and the right-arrow key for rightward motion. Participants were given feedback about the number of trials completed after they had completed 25%, 50%, 75%, 90% and 100% of the experiment, but they were not given any feedback about their performance. At the beginning of the experiment, participants were instructed to maintain fixation on the dot that constituted the nose of the face. They were warned that looking directly at the line would make the task more difficult. It was then emphasized that the direction of gaze in the cartoon face was irrelevant for their task, that it gave no information about the direction of motion of the line, and that they should ignore it.

2.3. Results

For each direction of attention (left, right and straight-ahead) and SOA, a cumulative normal curve was fit by a maximum likelihood procedure to the fraction of perceived rightward motion across the seven velocities. The psychophysical curves of all the participants for the 300 ms SOA condition are plotted in Fig. 2. The mean of the fitted functions determined the 50% threshold, that is the velocity that corresponds to perceiving rightward motion 50% of the time (i.e. the point at which motion direction is most ambiguous). For each participant, we assessed the effect of directing attention to the right (respectively left) by computing a rightward (respectively leftward) bias. This bias was obtained by subtracting the 50% threshold of the straight-ahead condition from the 50% threshold of the right-gaze condition (respectively left-gaze condition). Data from experts and naïve subjects were collapsed as the level of expertise was not observed to affect the motion biases (Fig. 3, at SOA of 300 ms: right biases—naïve: 15.2 ± 3.6 ms, experienced: 14.9 ± 3.2 ms, $p > 0.95$; left biases: naïve: -13.2 ± 2.8 ms; experienced: 8.7 ± 1.3 ms, $p > 0.25$; all of the subjects showed the effect in the direction of the mean).

First, the analysis focused on the 300 ms SOA to confirm the presence of a line-motion illusion when RGO is used as an attentional cue. Fig. 4 shows that when participants attended to the right, a bias of +15.1 ms (SEM = 2.4) was observed indicating that motion to the right needed to be added to the line for participants to be maximally uncertain about direction of motion (two-tailed $t(9) = 6.25$, $p < 0.0001$). Similarly, when participants attended to the left, a bias of −11.4 ms (SEM = 1.85) indicated that motion to the left had to be added to the line for participants to be maximally uncertain about direction of motion (two-tailed $t(9) = 6.18$, $p < 0.0001$). These findings confirm a reliable line-motion illusion.

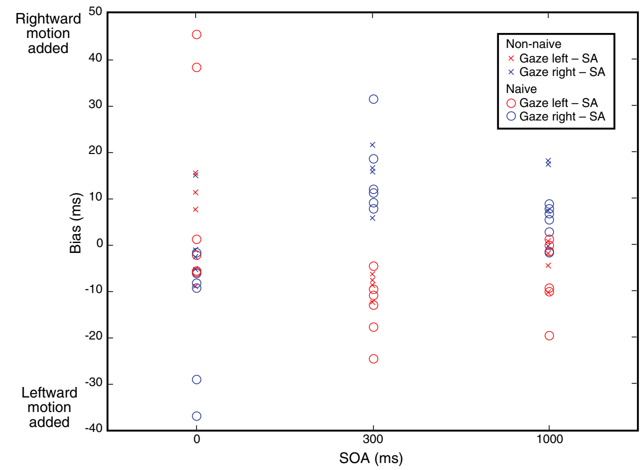

Fig. 3. Scatter plot indicating the range of the individual right-gaze and left-gaze biases, computed as the difference in shifts between the gaze straight-ahead (SA) condition and the right-gaze (left-gaze) conditions. Each bias is reported separately as a function of the time delay between the presentation of the attentional gaze cue, the pupils, and the appearance of the line (SOA) in Experiment 1. Data from naïve and experienced participants are comparable. As expected, the biases were inconsistent at an SOA of 0 ms before attention could be reoriented. At 300 ms, and to a lesser extent at 1000 ms, individual biases were clearly influenced by the location of attention.

Next, the analysis tested the hypothesis that the size of the effect varied with the SOA. An ANOVA on the values of the right and left biases was performed with SOA (0, 300 and 1000 ms) and attention direction (right, left) as factors. A weak main effect of attention direction was observed, confirming different biases as attention switched from left to right ($F(1,9) = 5.1$; $p < 0.05$). In the right-gaze condition, a bias of +4.63 ms indicated that motion to the right needed to be added to the line such that participants were maximally uncertain about the direction of motion of the line in that condition. In the left-gaze condition, a bias of −2.36 ms showed the opposite trend. More importantly, however, an interaction between SOA and attention direction indicated that the effect of attention on the motion biases differed as a function of SOA ($F(2,18) = 10.8$; $p < 0.001$). Separate two-tailed t-tests for each SOA and attention direction indicated that the biases were not significantly different from zero at the SOA of 0 ms, but robustly different from zero at SOAs of 300 and 1000 ms (Figs. 3 and 4).

To more directly assess our hypothesis that the biases were caused by attention and thus followed the time course of attention, we performed planned comparison between the 0 and 300 ms SOA conditions and between the 300 and 1000 ms SOA conditions. The bias observed under right-gaze attention (respectively left-gaze

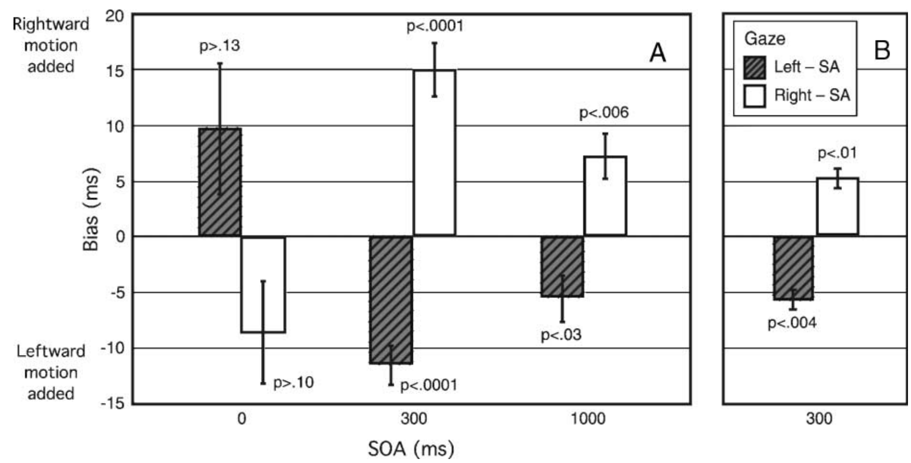

Fig. 4. (A) Mean right-gaze and left-gaze biases in Experiment 1, as a function of the time delay between the presentation of the attentional gaze cue and the appearance of the line (SOA). Each bias was compared to a mean of zero; the corresponding two-tailed p values are shown. As predicted, the strength of the bias followed the known dynamics of gaze-oriented attention with no effect at 0 ms, maximal at 300 ms and diminished at 1000 ms. (B) Right-gaze and left-gaze biases in Experiment 2 when eye movements were monitored.

attention) was greater at 300 ms than 0 ms SOA (two-tailed $t(9) = 3.9$, $p < 0.004$, respectively $t(9) = 3.0$, $p < 0.015$). Similarly, the bias observed under right-gaze attention (respectively left-gaze attention) was larger at 300 ms than 1000 ms (two-tailed $t(9) = 2.93$, $p < 0.017$, respectively $t(9) = 3.6$, $p < 0.006$). These findings support the proposal that the perceived direction of motion is altered by attention, as gaze-directed attention is known to be greatest around 300 ms.

2.4. Discussion

Experiment 1 confirms a reliable line-motion illusion when RGO is used, indicating that attention alone can lead to a switch in perceived direction of motion. As predicted by the time course of RGO, this effect was greatest at 300 ms SOA, smaller but still significant at 1000 ms SOA, and non-existent at 0 ms SOA. Thus, the strength of the illusion matches well the known dynamics of RGO, supporting the view that attention is driving these changes in perceived direction of motion. The lack of motion biases at 0 ms SOA demonstrates that these motion biases are not due to a general response bias by which participants, when uncertain, systematically prefer to indicate motion away from the gaze orientation. Indeed, even at 0 ms SOA, participants have ample time to process the direction of gaze before indicating their answers, as their reaction time was on average 723 ms after the initiation of the trial. This point is strengthened by the finding of lesser motion bias at 1000 ms SOA than at 300 ms SOA. Thus, Experiment 1 suggests that RGO can lead to a robust line-motion illusion, and demonstrates that the presence and strength of the illusion follows the known dynamics of that type of attention.

Before concluding that attention alone can lead to a switch in perceived direction of motion, there are alternative explanations that deserve consideration. The first one concerns eye movements. Although participants were urged to not move their eyes, it is possible that RGO triggers a bias for participants to move their eyes where the direction of gaze points. This is a concern since stronger motion biases have been reported away from the direction of gaze of participants (see Hecht (1995) as cited in Schmidt (2000)). Given the time it takes to program, initiate and complete an eye movement, participants would be most likely to land in the vicinity of the attended side of the line around 200–300 ms after the initiation of the trial; in other words, a few milliseconds before the line is drawn in the 300 ms SOA condition. If motion is more likely to be seen away from where the eyes fixate, eye movements could indeed explain the motion biases seen at 300 ms SOA. They would also account for the lack of motion biases at 0 ms SOA as the eyes would not have had time to move before the line is drawn in this condition. Finally, the weaker bias at 1000 ms SOA would be consistent with the fact that, in this condition, the line is drawn a long time after the eye movement triggered by the gaze would be completed, allowing ample time for other fixations. Experiment 2 controls for the role of eye movements in the motion biases observed by using an eye-tracker.

3. Experiment 2

The goal of Experiment 2 was to assess the contribution of eye movements to the bias in perceived motion direction described in Experiment 1. We reasoned that, if the motion biases found at 300 ms SOA are principally due to eye movements rather than attention, these biases should disappear when strict fixation is enforced during each trial.

3.1. Participants

Twelve naïve participants were included in this study. All participants received monetary compensation for their participation. Two subjects had to be discarded because of their inability to perform the task (flat psychometric functions); another one because of excessive eye movements (more than 50% of the trials). The remaining nine subjects included six females and had a mean age of 20.5 years (range: 18–24 years).

3.2. Methods

Stimuli, apparatus and procedure were identical to Experiment 1 except for the following modifications. A Sony GDM-FW900 23 in. monitor (Sony Electronics, Inc., New York, NY) was used. To allow for eye tracking, subjects viewed the monitor at a distance of 53 cm. All stimuli were increased in size to maintain the same visual angle as in Experiment 1.

Unlike in Experiment 1, only the 300 ms SOA condition was used. The experiment included a total of 630 trials (= 3 location of attention × 7speed × 30 trials) for a duration of about 1 h.

3.2.1. Monitoring eye position

Monocular left eye position was monitored with an Applied Science Laboratories 504 eye-tracker (Bedford, MA), a remote, video-based eye-tracker that uses a ring of near-infrared LEDs to illuminate the eye and capture the beam reflected from the cornea.

The raw measurements obtained are the separations between the pupil centers and the corneal reflections. From these raw data, the direction of gaze can be retrieved given adequate calibration. The ASL 504 reports the gaze position as the X–Y intersection of the line-of-sight with the working surface, whose position and orientation are entered into the ASL during calibration. The eye position signal was sampled at 60 Hz. The accuracy of the ASL's eye signal is approximately 0.5° over a central 40° field. A standard nine-point calibration was performed over a region of 15.6° by 15.6° at the beginning of the experiment. The accuracy of this calibration was monitored throughout the experiment. Although this system can compensate for head movements using its pan/tilt eye camera optics module, a chin rest was used throughout the experiments to minimize possible drifts in calibration. Participants were given the opportunity to rest in the middle of the experiment. This caused the calibration to shift slightly in a few subjects, and was corrected by applying the required offset correction manually.

A circle with a radius of 1° of visual angle was defined around the fixation point (the nose of the face as in Experiment 1). Trials in which a participant's gaze deviated from that area during the trial period were not included in the analysis. The trial period began at the onset of the trial and lasted for 500 ms, requiring subjects to maintain fixation for at least 175 ms after the line had been fully presented.

3.3. Results

As in Experiment 1, a right and a left bias were computed by subtracting the threshold for straight-ahead from that for right and respectively left-gaze conditions. An analysis comparing the right and left bias confirmed that they were statistically different from each other ($F(1,8) = 26.1$, $p < 0.001$). Two-tailed t-test were used to confirm that the right bias and the left bias were significantly different from zero (mean of 5.1 ms (SEM = 1.5), $t(8) = 3.33$, $p < 0.01$ and mean of −5.4 ms (SEM = 1.4), $t(8) = 3.91$, $p < 0.004$ respectively). Thus, even in the absence of eye-movements, RGO was observed to bias the perceived direction of motion.

On average, 10.2% of the trials were discarded because of eye movements (mostly due to small deviations outside of the defined area, but also loss of signal due to lenses, glasses or dry eyes, and some saccades downright toward the line). There was, however, a large range in the ability of subjects to maintain fixation (only 2.1% of the trials were discarded in the best subject versus 35.2% in the worse subject). To further confirm that eye movements play little if any role in the results described above, we compared biases estimated using all trials to biases estimated using only trials without eye movements. The biases observed did not differ across analysis (right biases comparison: $p > 0.5$; left biases comparison: $p > 0.18$) confirming that the inclusion of trials with eye movements cannot easily account for the results of Experiment 1.

3.4. Discussion

As in Experiment 1, subjects had a tendency to see the static line as being drawn away from the right side when attending to the right, and away from the left side when attending to the left, even though fixation was maintained centrally for at least 175 ms after the line had been drawn. Since subjects remained fixated centrally and trials with eye movements were discarded, the bias observed in this experiment cannot be explained by eye movements. This finding is in agreement with a report by Schmidt (2000) that the line-motion illusion is not an artifact of eye movements. We also showed that the size of the bias is not modified when trials in which eye movements occurred are included supporting the view that artifacts from eye movements cannot explain the line-motion illusion effects observed in Experiment 1. Interestingly, the size of the biases in Experiment 2 was smaller than in Experiment 1 (left bias: means of 11.4 versus 5.4 ms, $p < 0.02$; right bias: means of 15.1 versus 5.1 ms, $p < 0.004$). The source of this effect is unclear, although the combination of naïve subjects and eye tracking may have conspired to produce smaller biases in Experiment 2. A pilot version of Experiment 2 that had been run on a few experienced subjects revealed stronger motion biases than in the naïve subjects. It is possible that when eye movements are monitored, naïve participants (which are less trained at fixating) tend to be more focused on the fixation point, and thus devote more of their attention at that location. This could have resulted in a smaller effect of gaze-directed attention in Experiment 2 for naïve participants, whereas they showed the same biases as experienced participants in Experiment 1. Overall, the observation of significant motion biases in Experiment 2 in which trials with eye movements were excluded rules out the possibility that the line-motion illusion is due to eye movements.

Although the experiments presented so far point to a role of attention in the line-motion illusion, it could be the case that attention does not change the perception of the direction of motion as proposed. Rather one could argue that the effects reported are due to response biases. Experiments 1 and 2 employed a 2AFC procedure in which participants were required to indicate a direction of motion, even if they did not perceive any motion. When forced to generate a response when uncertain, the participants could be easily influenced by any small factors, such as the direction of the attentional cues. A simple response bias could be present, in which participants were simply more likely to report motion direction away from the locus of their attention at the time of the response. Such a response bias predicts the same motion biases at all SOAs, and is thus ruled out by Experiment 1. However, a more sophisticated response bias is also possible. Observers may be more likely to indicate motion away from the locus of their attention at the time the line was drawn. Such a response bias predicts no motion bias at a 0 ms SOA, as attention has had no time to shift to the end of the line when it is presented, but significant motion biases at 300 and 1000 ms SOAs as reported in Experiment 1. To eliminate response biases that might be present in a 2AFC procedure, we designed Experiment 3 to measure the participants' perception more directly. In this experiment, participants reported their perception of the strength of the motion in the line rather than indicating a forced choice about the motion direction.

4. Experiment 3

As in previous experiments, participants were presented with displays including various amounts of motion. However, in this experiment participants were asked to rate the strength of the motion in each display. As before, seven levels of motion were sampled (three to the right, three to the left and static). The velocities used were chosen so that the conditions spanned from a clear percept of no motion (line drawn in 1 frame) to a strong motion percept (line drawn in 7 frames). This choice ensured that participants would experience unambiguous motion percept during the experiment, allowing participants to have a clear perceptual anchor to guide their subjective ratings of motion strength.

Of key interest for our purpose was the rating of static displays as the location of participants' attention was directed either straight-ahead (control condition) or to the left or right (experimental conditions). If attention can lead to motion perception, higher motion ratings should be observed when attention is directed left or right than when it is directed straight-ahead. Importantly, this rating task focused on the strength of the motion in the line independently of the direction of the motion. Thus, unlike in the previous experiments, the response dimension was independent of the location of attention, ensuring minimal contribution of a response bias that might co-vary with attention location.

4.1. Participants

Eight naïve observers participated in this experiment and received monetary compensation. The participants included seven females and had a mean age of 19.5 years (range: 18–25 years).

4.2. Methods

Apparatus and stimuli: The same apparatus as in Experiment 1 was used. The stimuli were identical to those of Experiment 1 except that only one SOA of 300 ms was used.

Procedure: Participants were asked to report, for each display, the strength of motion in the line on a scale of 1–4 where 1 corresponded to no motion and 4 to clear motion. The procedure was otherwise identical to that of Experiment 1.

Design: As in Experiment 1, the cued location (left, right or straight-ahead) and velocities (static, or delays of 12.5, 25 or 37.5 ms to the left or right) were counterbalanced and randomly mixed across trials. Each condition was repeated 30 times for a total of 630 trials.

4.3. Results

Of primary interest for our purpose were motion ratings when the line was static as a function of attentional status (left or right versus straight-ahead gaze). Mean rating for static display when attention was straight-ahead was 1.84 (SEM = 0.17) versus a mean rating of 2.08 (SEM $= 0.14$) when attention was directed either left or right. The motion strength under the right-gaze (2.16, MSE $= 0.2$) and the left-gaze condition (1.98, MSE $= 0.15$) were not statistically different from each other (two-tailed $t(7) = 1.5$, $p > 0.16$), in accordance with the view that the ratings of motion strength should be independent of attention direction. For each participant, the differences between left and straight-ahead gaze and between right and straight-ahead gaze were computed and entered in a 2-way within-subject ANOVA. The mean rating difference was of 0.24 (SEM $= 0.07$; $F(1,7) = 9.53$, $p < 0.018$) indicating greater a motion percept for the left and right-gaze conditions than the straight-ahead gaze condition. The conditions in which motion was added to the line were then analyzed by grouping those conditions in which the line-motion illusion predicted more motion (leftward motion with attention to the right and rightward motion with attention to the left) and those in which the line-motion illusion predicted less motion (leftward motion with attention to the left and rightward motion with attention to the right). An ANOVA was performed on the rating strengths with predicted motion strength (two levels: less and more) and line delay (three levels: 12.5, 25 and 37.5 ms) as factors. No effects of attention were observed ($p > 0.35$). The finding of an attentional effect with static displays but not with moving ones is not entirely surprising as the difference between a static display and a moving one is likely to be more salient to observers than would a small change in perceived velocity. The results from the conditions in which motion was added confirmed that participants' ratings of motion increased as the amount of motion in the line was increased ($2.14 - \text{MSE} = 0.1$, $2.35 - \text{MSE} = 0.06$ and $2.69 - \text{MSE} = 0.06$ as motion increased; $F(2,14) = 20.9$, $p < 0.0001$). This finding establishes that participants were indeed complying with the task requirements.

4.4. Discussion

Experiment 3 establishes that participants perceive static displays as having more motion when attention is oriented toward the extremities of the static line than when it is oriented neutrally. Because motion perception was assessed directly, and because the response options were not confounded with the direction of attention, the contribution of response biases is unlikely in this experiment. Thus it appears that attention alone can bias the percept of a static line into a moving one.

5. General discussion

This series of experiments establishes that attentional factors alone are sufficient to induce the line-motion illusion. By using RGO, we were able to rule out any contributions from sensory facilitation and apparent motion in this phenomenon. This finding supports and furthers previous studies whose goals were to rule out the contribution of these factors in the illusion. For example, Hikosaka et al. (1993c) have shown that voluntary attention is sufficient to induce the line-motion illusion. However, this result has been challenged as a few investigators failed to observe the illusion when manipulating voluntary attention (Downing & Treisman, 1997; Klein & Christie, 1996). A more recent report suggests that endogenous attention can induce the line-motion illusion (Schmidt, 2000). The effect is weaker than with exogenous attention and highly sensitive to experimental manipulations. In particular, it seems to rely on the close proximity between the line and the sensory cue that endogenously orients attention. Such spatial constraints could be consistent with an explanation of the illusion in terms of impletion between the attentional cue stimulus and the spatially contiguous line. The finding that the line-motion illusion is observed with the use of lateral auditory or tactile cues has also been used to argue against the role of apparent motion in the manifestation of the illusion (Shimojo et al., 1997). However, apparent motion can occur between auditory and visual stimuli (Zapparoli & Reatto, 1969), permitting a possible role for apparent motion in this result. Finally, there is one report that the line-motion illusion can be generated by expectation or memory, suggesting that the illusion can occur without invoking apparent motion mechanisms (Shimojo, Miyauchi, & Hikosaka, 1993). However, this effect was only seen after extensive training and relied upon the use of a 2AFC procedure, that can be potentially contaminated by significant response biases (Shore, Spence, & Klein, 2001). The present series of studies addresses these concerns. First, by showing that the strength of the line-motion illusion co-varies with the known dynamics of RGO, it establishes the participation of attention in this illusion. Second, unlike previous studies, the line-motion illusion in these experiments was observed in the absence of visual stimuli near the extremities of the line, ruling out any contribution from apparent motion. Third, the observation in Experiment 3 of a change in the strength of the motion percept as a function of attention location suggests that the illusion cannot be entirely attributed to response biases. It is worth noting that response biases are a concern when using a forced choice task especially when the subjects are not blind to the goal of the experiment. Although in Experiment 1 naïve participants did not differ from lab members, in a preliminary version of Experiment 2, lab members—who, by that time, had been exposed through lab meetings to the goal of the study—were observed to have greater illusion than naïve participants. The use of several SOAs in Experiment 1 may have minimized response biases from knowledgeable subjects. This observation led us to include only naïve participants in Experiments 2 and 3. Overall, our observation matches that of Schmidt (2000) in showing that familiarity with the illusion is not necessary to observe the illusion, but that, under certain circumstances, it can contribute to greater effects.

The three studies presented establish that visual attention is sufficient to produce the line-motion illusion. This does not suggest that apparent motion or impletion mechanisms do not play a role in the illusion when sensorily defined cues are used, as is the case in most of the studies reported so far. As illustrated by some studies (Downing & Treisman, 1997; Grunau & Faubert, 1994; Kawahara et al., 1996), it is likely that apparent motion processes do contribute to the illusion. Anecdotal observations from our laboratory also confirm that view. Indeed, the percept of motion is extremely robust when using exogenous cues, but more subtle when using reflexive orienting.

As originally proposed by Hikosaka and collaborators (1993a), the line-motion illusion may be due to an increase in processing speed at the attended location. The attended side of the line would then be processed faster than the unattended one; this timing difference would be interpreted as a motion signal by motion-sensitive areas such as MT and MST. A very similar model developed by Schmidt and Klein (1997) to account for further line-motion effects postulates not only accelerated transmission of attended signals but also extended duration of their transmission. These models share the assumption that the effect occurs at an early stage of visual processing. An alternative account that does not call for changes at the early stages of visual processing could also account for our results (see Schneider (2001) for evidence against the view that attention accelerates visual processing). Indeed, the present results may be an instance of 'third-order' motion first described by Sperling and collaborators and also termed 'attention-generated apparent motion' (Sperling & Lu, 1998). This class of motion is different from the standard apparent motion discussed earlier. Whereas standard apparent motion relies on an impletion mechanism during which the visual system links by inference two distinct objects into a single moving one, third-order motion does not rely on the binding of objects over space and time. Third-order motion is motion induced by differences in saliency maps over time and space (Lu & Sperling, 1995). In this view, the relative importance of each point in the image is attributed a salience value, and a flow field is continuously computed by estimating the direction and magnitude of the salience movement at each point in time. In our case, motion in the line would be perceived as a result of changes in the saliency of the different part of the lines. As proposed by Sperling and collaborators, this effect is likely to be mediated by higher visual areas such as the parietal cortex, rather than early sensory stages (Sperling & Lu, 1998).

Overall, our findings indicate that the line-motion illusion can be perceived even when sensory facilitation and apparent motion mechanisms are ruled out. Although several mechanisms may account for the effect we report, its observation in naïve participants with such a simple manipulation as that of reflexive attention suggests that we may be subject to such motion illusion in all aspects of our every day life.

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