Atten Percept Psychophys
DOI 10.3758/s13414-011-0239-y

Spatial mislocalization as a consequence of sequential coding of stimuli

Heinz-Werner Priess · Ingrid Scharlau ·
Stefanie I. Becker · Ulrich Ansorge

Abstract In three experiments, we tested whether sequentially coding two visual stimuli can create a spatial misperception of a visual moving stimulus. In Experiment 1, we showed that a spatial misperception, the *flash-lag effect*, is accompanied by a similar temporal misperception of first perceiving the flash and only then a change of the moving stimulus, when in fact the two events were exactly simultaneous. In Experiment 2, we demonstrated that when the spatial misperception of a flash-lag effect is absent, the temporal misperception is also absent. In Experiment 3, we extended these findings and showed that if the stimulus conditions require coding first a flash and subsequently a nearby moving stimulus, a spatial flash-lag effect is found, with the position of the moving stimulus being misperceived as shifted in the direction of its motion, whereas this spatial misperception is reversed so that the moving stimulus is misperceived as shifted in a direction opposite to its motion when the conditions require coding first the moving stimulus and then the flash. Together, the results demonstrate that sequential coding of two stimuli can lead to a spatial misperception whose direction can be predicted from the order of coding the moving object versus the flash. We propose an attentional sequential-coding explanation for the flash-lag effect and discuss its explanatory power with respect to related illusions (e.g., the Fröhlich effect) and other explanations.

Keywords Attention · Visual illusions · Prior entry

At every moment in time, a multitude of visual stimuli impinge on the human retina, but only a few of these stimuli are selected for purposes such as perception, in-depth processing, or action control. Attending to different visual locations, stimuli, features, or dimensions boosts the perception and discrimination of fine visual detail (cf. Bashinski & Bacharach, 1980; von Helmholtz 1894) and speeds up processing of visual stimuli at the focus of attention, as well as subsequent saccades to the attended stimuli (cf. Posner, 1980; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). At the same time, attending can prolong the perceived duration of the attended stimuli (cf. Enns, Brehaut, & Shore, 1999; Mattes & Ulrich, 1998).

Apart from these effects, visuospatial attention can also contribute to visual illusions. As everyday observers, we are barely aware of these illusions. We naively presume that the temporal and spatial features that we perceive reflect the physical properties of distal objects. Beginning with the early days of experimental psychology, however, visual illusions have shown that spatial features of distal objects can be misperceived (e.g., Fröhlich, 1929), and related research has suggested that attention could be (partly) responsible for these effects (Müsseler & Aschersleben, 1998). Fröhlich observed that the starting position of an abruptly onsetting moving stimulus was not veridically perceived. Instead, it was perceived at a position shifted

---

H.-W. Priess (✉) · U. Ansorge
Faculty of Psychology, University of Vienna,
Liebiggasse 5,
1010 Wien, Austria
e-mail: heinz-werner.priess@univie.ac.at

I. Scharlau
Department of Cultural Sciences, University of Paderborn,
Paderborn, Germany

S. I. Becker
School of Psychology, University of Queensland,
Brisbane St Lucia, Australia

U. Ansorge
Faculty of Psychology, University of Vienna,
Wien, Austria

farther along its motion trajectory. According to Müsseler and Aschersleben, visual perception of the onset position of the abruptly onsetting moving stimulus depends on allocating attention to its position and is therefore beset with a delay corresponding to the time it takes for attention to focus on the moving stimulus. As a consequence, the moving stimulus will have a perceived onset location that is shifted in the direction of the stimulus movement (cf. Fröhlich, 1929). In line with this assumption, several studies have shown that the Fröhlich effect is reduced when attention is allocated earlier to the motion onset—for instance, when the position of the abruptly onsetting motion stimulus is precued (cf. Ansorge, Carbone, Becker, & Turatto, 2010; Müsseler & Neumann, 1992; Müsseler, Stork, & Kerzel, 2008).

These results reveal that perceptual illusions caused by visuospatial attention may be the flip side of the advantageous effects of visuospatial attention: Because the focusing of visuospatial attention is a necessary precondition for an in-depth representation of a visual stimulus, attention can also delay the perception of a stimulus if it is initially misdirected elsewhere. This role of attention as a gatekeeper for perception is also supported by another type of illusion: Selective attention can also modulate visual illusions concerning the temporal features of visual objects. In this case, the misperception caused by attention is often even more difficult to detect. For example, in the complication experiments, Wundt (1896) noted that his subjects perceived predictable rhythmic stimuli faster than unforeseeable stimuli. In these experiments, participants saw a clock with a rotating hand and had to rate the time at which they heard or felt a stimulus by indicating the clock hand position at the time of the perception of the heard or felt stimulus. Perceptual latency was lower when the stimuli were repeatedly presented at a rhythmic interval. Wundt and other researchers ascribed this effect to prior entry: Focusing attention on a stimulus facilitates stimulus perception so that an attended stimulus is perceived earlier than an unattended stimulus. Because attention can be focused better on an expected rhythmically repeated stimulus than on a stimulus that cannot be anticipated, perception of the rhythmic stimulus is faster than that of the unanticipated stimulus. Already in Wundt's times, this interpretation was criticized as reflecting a judgment bias (cf. Dunlap, 1910), but it was later rehabilitated in light of more rigorous experiments (e.g., Shore, Spence, & Klein, 2001; Stelmach & Herdman, 1991).

The transient focusing of visuospatial attention could thus be a mechanism for modulating temporal, and possibly also spatial, misperceptions or illusions. The mere duration of the attention shift from A to B might be responsible for a spatial misperception—for example, when stimulus B is a moving stimulus and moves along its trajectory while attention is first focused on A, such that attention can only catch up with B at a later point on its motion trajectory (cf. Baldo & Klein, 1995; Müsseler & Aschersleben, 1998). However, it is also possible that attention has a different effect and creates illusions by serving as a temporal marker for a point of reference for the beginning of a visual representation that is integrated over a certain duration *X* (e.g., Becker, Ansorge, & Turatto, 2009). According to this line of thinking, attending to one stimulus A provides the starting point for the integration of visual information from this (e.g., moving) stimulus, such that the representation of the position of a moving stimulus would be defined by a time window of some minimal duration (e.g., 80 ms) after the focusing of attention on A (cf. Eagleman & Sejnowski, 2007). This kind of temporal marking of a reference point by attention plus the integration of visual evidence over time elegantly explains the Fröhlich effect, that the position of a moving stimulus is misperceived in the direction of motion and can also account for the flash-lag effect (cf. Nijhawan, 1994). The latter effect denotes the misperception of a moving stimulus as shifted in the direction of its motion when it is in fact objectively aligned with a visual flash (Eagleman & Sejnowski, 2000b).

However, it should be noted that factors besides attention can contribute to sequential coding and spatial misperceptions. For instance, in the Fröhlich effect, the initial position on the motion trajectory (and, in fact, each subsequent position on the motion trajectory alike) is not only difficult to attend to: The perception of this position is also delayed because it is subject to visual backward masking or metacontrast masking (cf. Breitmeyer & Ogmen, 2006) by the subsequent visual stimulus at the next adjacent position along the motion trajectory, which could result in a decreased visibility of the onset position (cf. Carbone & Ansorge, 2008; Kirschfeld & Kammer, 1999). Hence, the Fröhlich effect could also be a consequence of masking; that is, the initial position of a moving stimulus is seen as shifted in the direction of motion because the initial position is backward masked and does not benefit from prior position priming by a preceding adjacent stimulus on the trajectory, as would be the case for all subsequent positions but the initial position of the moving stimulus. Likewise, in the flash-lag effect, factors such as the exact contrast of the flash as compared with that of the moving stimulus, and the resultant temporal head start of the processing of one stimulus over the other, determine the extent of the spatial illusion (Purushothaman, Patel, Bedell, & Ogmen, 1998). The uniting principle of all of the different mechanisms, however, seems to be the principle that the temporal precedence of the processing of one stimulus, position, or feature over the other can lead to spatial misperceptions, and that attention is but one way in which this sequential coding could be brought about. In the present study, we tested the possibility that sequential coding in general (Exps. 1 and 2) and attention in particular (Exp. 3) could be responsible for spatial misperceptions.

Experiment 1

If a spatial misperception, such as the flash-lag effect, is indeed due to the sequence of the participants' coding first the flash and subsequently an aligned moving stimulus (here, a bar), then we would expect to find that the participants also perceive the flash as temporally preceding the aligned moving stimulus at the same position, even if the two stimuli are presented synchronously at this position. This prediction will be tested in Experiment 1, in which we adapted a procedure for the measurement of the flash-lag effect (Kerzel, 2010; Nijhawan, 1994).

In studies on the flash-lag effect, participants have to judge the position of a moving bar relative to that of a flash. In this situation, despite the fact that the two stimuli, flash and moving bar, are objectively exactly aligned, the flash is usually perceived to be "lagging" behind the moving bar (flash-lag effect; Nijhawan, 1994). To test whether under these conditions the flash is also (mis)perceived to precede the moving bar in time, we had to introduce a visual change of the moving bar. The time of this change could then be compared with the time that the flash was presented. For that purpose, the moving bar changed its appearance near the time of the flash. As a consequence, we were able to ask our participants for their judgments about the spatial position of the moving bar relative to the flash in one block, and to report the temporal order of the time of the change of the moving bar relative to the presentation of the flash in another block.

If the sequential coding first of the flash and then of the moving bar is responsible for the spatial misperception of the moving bar, we should find (a) a spatial flash-lag effect in the spatial judgment task, with the moving bar perceived as shifted in the direction of its motion relative to the position of the flash, when in fact the moving bar and the flash are objectively exactly aligned, and (b) a temporal flash-lead effect in the temporal judgment task, with the flash perceived as appearing earlier than a change of the moving bar, when in fact the onset of the flash and the change of the moving bar are objectively exactly synchronous.

Method

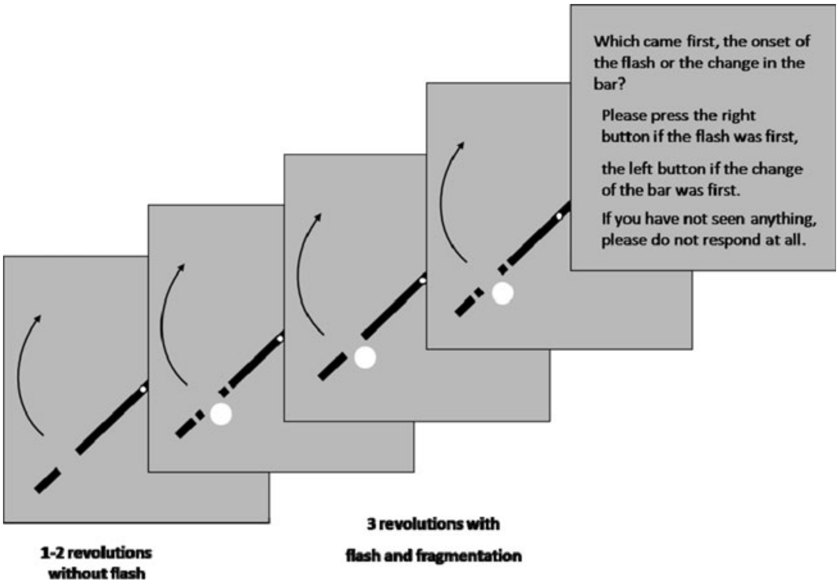
Participants A group of 15 participants participated in the temporal and spatial judgment tasks of Experiment 1. All participants had normal or corrected-to-normal vision, based on prior testing. Two of the participants had to be excluded because their judgments did not vary as a function of the stimulus onset asynchrony (SOA) between flash and change of the bar. Participants were naïve with respect to the experimental hypotheses, and all gave informed consent.

Materials An Intel Core 2 Duo 2.80-GHz computer with a 19-in. color monitor (Iiyama HM903DT Vision Master Pro) controlled the timing of events and generated the stimuli. Stimuli were presented with a resolution of 1,024 × 768 pixels and a refresh rate of 75 Hz. Participants viewed the screen from a distance of 57 cm, with the head supported by a chinrest. For registration of manual responses, we used a standard keyboard. Event scheduling and response measurement were controlled by MATLAB and the Psychophysics Toolbox (Brainard, 1997).

Stimuli See Fig. 1 for a depiction of the procedure in a trial. The rotating bar was a black (0.5 cd/m^2) bar centered on the gray (4 cd/m^2) screen. It had a length of 10.7º and a width of 0.5º. The bar rotated with a speed of 50 cycles per minute, with its axis of rotation at screen center. With every refresh of the monitor (13.3 ms), this bar rotated by 4.0º angle of rotation. The rotating bar had two gaps, one near each of its ends. At one point during the revolutions of the bar, flashes were presented within these gaps. The gaps had a length of 1.1º and were located with an eccentricity from the gap's center of 3.4º. Because the diameters of the circular flashes were equal to the gap lengths, each flash fitted into the gap if it was presented aligned with the rotating bar. The flashes were two white disks (118 cd/m^2), both with a diameter of 1.1º and presented with the same eccentricity as the gaps: With respect to screen center as a point of reference, the two flashes were presented at point-symmetrically opposite positions for a single refresh of the computer screen.

For the visual change of the rotating bar, this bar was repeatedly fragmented and completed: During one revolution, two segments of the rotating bar with lengths of 0.4º vanished near the gaps of the rotating bar, and during the next revolution, these segments reappeared. A demo of Experiments 1 and 2 can be found at http://pptypo3.univie.ac.at/fileadmin/usermounts/priessh9/FLE_TOJ/FLE_TOJ.html (Priess 2011).

Design and procedure The experiment consisted of two blocked conditions, a temporal judgment task and a spatial judgment task, that were identical with respect to the stimuli. The blocks were counterbalanced across participants. In each trial of both the spatial and temporal judgment tasks, participants had to fixate on a small white dot at the center of the screen, and they initially saw one to two revolutions of the rotating bar. After this, the flashes



Which came first, the onset of the flash or the change in the bar?

Please press the right button if the flash was first,

the left button if the change of the bar was first.

If you have not seen anything, please do not respond at all.

Fig. 1 Depicted is a schematic illustration of the sequence of displays (frames from left to right) in a trial of Experiment 1. A trial started with the presentation of the moving bar (in the frame on the lower left of the figure). After a variable time (one or two revolutions of the rotating bar), two flashes (white disks) were shown. At or near the flash-onset time, the rotating bar was fragmented or completed (depending on how the bar looked at the beginning of the trial). This is depicted in the second frame from left. A trial continued with another three revolutions, during which the flash was repeated and the bar was fragmented and completed in turn (in the third and fourth frames from the left). Participants had to either judge the spatial position of the flash relative to the rotating bar—this was the spatial task (not depicted)—or judge the temporal sequence between the onset of the flash and the change (segmentation or completion) of the rotating bar. An example of the concluding display in the temporal task is depicted (in the frame on the upper right). The arrows indicate the direction of motion. The stimuli are not drawn to scale

and the changes of the rotating bar were presented repeatedly for the three concluding full revolutions of the rotating bar during a trial. In this manner, participants were able to base their spatial and temporal judgments on their perception of one particular repeated temporal interval or spatial distance during all three concluding revolutions of the rotating bar in a trial.

The flashes were presented either spatially aligned with the rotating stimulus (0º) or with a spatial distance of an angle of rotation of 4.0º, 12.0º, 24.0º, or 48.0º away from the rotating bar. The unaligned flashes were equally likely to be shifted in the direction of the movement of the rotating bar or against it. In both blocks, orthogonally to the spatial distance manipulation, the flash could either temporally lead or lag the change of the rotating bar. Within a trial, the interval between the onset of the flash and the change of the rotating bar was fixed. The interval had a duration of 0, 13.3, 40, 80, or 160 ms. Each temporal interval thus exactly corresponded to one of the spatial distances—that is, the bar moved 4º in 13.3 ms, 12º in 40 ms, and so forth—to allow for comparisons between the magnitudes of the expected temporal and spatial illusions.

On half of the trials, the rotating bar was initially shown in complete fashion, and the first change of the rotating bar consisted of an offset of two small segments of the rotating bar (i.e., a fragmentation) during the first of the final three revolutions in this trial. On the other half of the trials, the rotating bar was shown segmented at the onset of rotation, and the first change consisted of the onset of the two missing segments (i.e., a completion). Across all conditions, onsets and offsets of segments alternated during subsequent revolutions (i.e., in the order onset, offset, onset or offset, onset, offset).

In the temporal judgment task, participants had to judge whether the flash was perceived temporally before the change of the rotating bar, or whether the rotating bar changed before the flash was presented. In the spatial judgment task, participants had to judge whether the flash was perceived at a position spatially shifted in the direction of the motion of the rotating stimulus or opposite to the direction of this motion. In the spatial judgment task, we used the nine different spatial distances for the calculation of the points of subjective equality (PSEs)—that is, the points of equal frequencies of the two judgments. In the temporal judgment task, we used the nine different temporal equivalents of the spatial distances for the calculation of the PSEs. Because every condition was tested 30 times, participants completed 270 trials in the temporal and spatial conditions, respectively.

Results

We used psignifit 2.5.6 to fit data to psychometric curves and to calculate the PSE for each participant and condition individually (Wichmann & Hill, 2001). Thereafter, two-tailed *t*tests were used to assess whether the spatial and temporal PSEs showed a perceptual illusion (i.e., significant deviations from zero).

As can be seen in the upper panel of Fig. 2, when flash and moving bar were presented spatially and temporally aligned, the flash was judged to spatially lag behind the moving stimulus on a majority of the trials. This corresponds to a spatial misperception in the form of a flash-lag effect: The flash had to be spatially located 10.3º (*SE* = 4.3º) ahead of the rotating bar in order to be perceived as being aligned at the same position as the bar, $t(12) = 8.42$, $p < .001$. This spatial shift of 10.3º corresponded to a delay of perception of the rotating bar relative to the flash of 34 ms (*SE* = 14 ms).

In the temporal judgment task, participants saw the change of the rotating bar as temporally lagging the onset of the flash: When the flash onset and the change of the moving stimulus were objectively simultaneous, the probability of reporting that the flash preceded the change of the rotating bar exceeded the expectancy value of $P = .5$. On average, the flash had to be presented 39 ms (*SE* = 29 ms) after the change of the rotating bar to be perceived as simultaneous. This temporal misperception—a temporal flash-lead effect—was also significant, as indicated by a mean PSE different from zero, $t(12) = 4.78$, $p < .01$.

If both the spatial and temporal misperceptions reflected the same underlying sequence of coding first the flash and then the rotating bar, the two misperception effects should be of equal magnitude. To test whether the temporal flash-lead and spatial flash-lag effects were of equal magnitude, we calculated the individual differences between the two misperception effects by subtraction of their time equivalents and performed a *t* test against zero with the difference values. The result of the *t* test was not significant: $t(12) = 0.55$, $p = .59$.

As can be seen in Fig. 2, however, the temporal task was more difficult than the spatial task. This is indicated by the fact that the average slope of the function was steeper in the spatial task (70 ms/inner quartile) than in the temporal task (15 ms/inner quartile). This slope difference was significant: $t(12) = 4.96$, $p < .01$. The steeper slope in the spatial task indicated better adherence with ideal performance (i.e., a step function) in that task than in the temporal task.

Discussion

In Experiment 1, we did indeed show that the same stimulus conditions that produced a spatial flash-lag effect also produced a temporal flash-lead effect. These results are in line with a sequential-coding explanation of the flash-lag effect: that participants first code the flash and delay coding of the moving object until it has moved farther along its

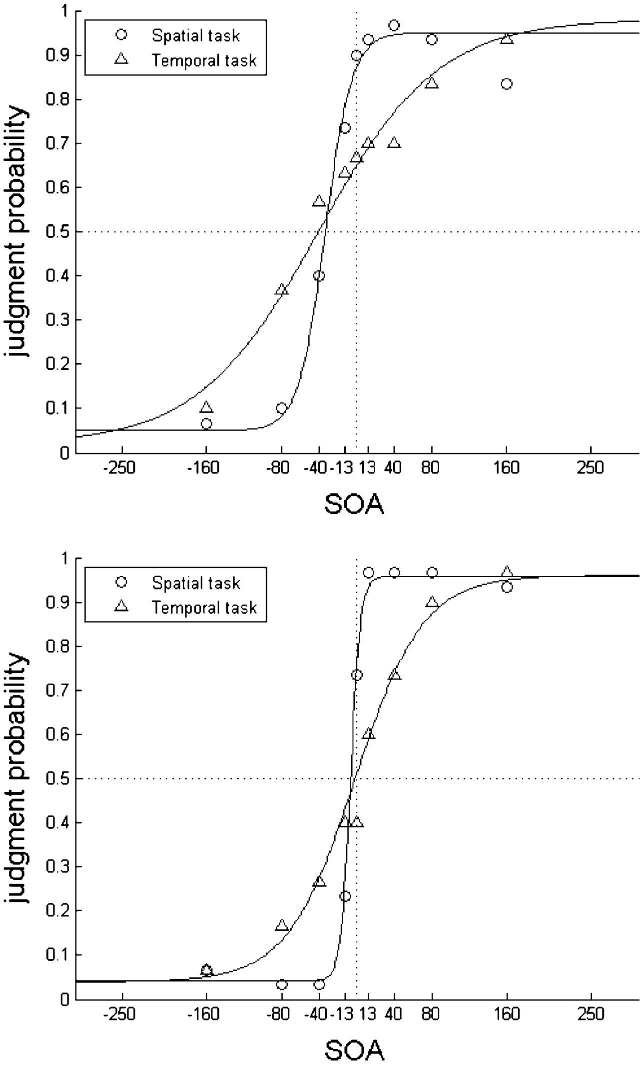


Fig. 2 Psychometric functions relating judgment probabilities on the *y*-axis to stimulus onset asynchronies (SOAs, in ms) on the *x*-axis, as a function of task (spatial or temporal) and experiment (Exp. 1, upper panel; Exp. 2, lower panel). In the spatial task, the *y*-axis depicts the probability of the judgment that the rotating stimulus was seen as shifted in motion direction (= flash was seen as shifted against the direction of the rotating stimulus), and the *x*-axis indicates the objective interval between the onset of the flash and the presentation of the rotating stimulus at the position of the flash. On the *x*-axis, a negative objective SOA in the spatial task means that the rotating bar objectively preceded the flash at the position of the flash. As can be seen, at the point of subjective equality (PSE; i.e., a judgment probability of $P = .5$) the SOA was negative in Experiment 1 (upper panel) but not in Experiment 2 (lower panel). This means a misperception in the form of a spatial flash-lag effect obtained in Experiment 1, but not in the control conditions in Experiment 2. In the temporal task, the *y*-axis depicts the probability of the judgment that the onset of the flash preceded the change of the rotating stimulus, and the *x*-axis shows the objective interval between the onset of the flash and the change of the rotating stimulus. On the *x*-axis, a negative objective SOA in the temporal task indicates that the visual change of the rotating stimulus objectively preceded the onset of the flash. As can be seen, at the PSE (judgment probability of $P = .5$) the SOA was negative in Experiment 1 (upper panel) but not in Experiment 2 (lower panel). This means a misperception in the form of a temporal flash-lead effect, obtained in Experiment 1 but not in Experiment 2

trajectory, which creates the impression that the flash lags behind. However, it is not yet certain whether sequential coding was indeed responsible for the spatial misperception. It could be argued that the sensory features of the rotating bar's motion (or position), on the one hand, and of the changes of the rotating bar, on the other hand, were not the same. For instance, theoretically, judgments about the position of the moving bar could always be based on the onset of the flash, but temporal judgments had to be based on the bar's offset at least for one revolution of the bar. Given the differences in the sensory features that could be used for the two different judgments, it is possible that the two illusions are based on different underlying mechanisms. At least, these differences make it difficult to link the temporal misperception of the change of the rotating bar closely to the spatial misperception created by the motion of the rotating bar.

Moreover, comparisons between the conditions are complicated by low-level feature differences between the conditions: First, note that the flash in Experiment 1 was white, whereas the bar was black. If processing a white flash is faster than processing a (change in a) black bar, the temporal precedence of the sensory processing of the white flash over the change in the bar could also account for the coding of the flash before the change of the bar. Second, the flash consisted of a fast onset–offset sequence, whereas the onsets and offsets of the bar were separated by a longer interval. If processing of an onset was faster than processing of an offset, or vice versa, participants could have always based their spatial judgments about the flash on the faster of these two features (e.g., onset of the flash), but would have been forced to base their temporal judgments about the change of the bar on the slower of the two features at least once per each trial (e.g., offset of segments).

What is needed to show that the temporal and spatial misperceptions are based on the same underlying mechanism is an additional joint manipulation of the illusions, this time with identical low-level features for the spatial and temporal decisions. This was done in Experiment 2.

Experiment 2

Experiment 2 critically tested whether the two misperceptions of a spatial flash-lag effect and a temporal flash-lead effect can be also manipulated in a predictable similar fashion (cf. Eagleman & Sejnowski, 2000a). Specifically, we expected that the sequence of first attending to the flash and then to the rotating stimulus should no longer be a preferred strategy when the moving bar stops at the time of the flash. This holds because if both flash and moving stimulus vanish at or near the point of their spatial alignment, the offsets of both stimuli can equally serve as a signal to start encoding the relative positions of these stimuli. This should eliminate the temporal flash-lead effect and, as a consequence, the spatial flash-lag effect.

In line with the second of these predictions, Eagleman and Sejnowski (2000b), among others, showed that the spatial flash-lag effect indeed disappears when a rotating stimulus stops its motion (and offsets) near or at the very moment that the flash appears and disappears. However, Eagleman and Sejnowski (2000b) did not test whether a temporal flash-lead effect was also absent under these conditions. If we are right that the more variable sequential-coding strategies (of either first the flash and then the rotating bar, in some trials, or first the offset of the rotating bar and then the flash, in other trials) are responsible for the absence of the spatial illusion in stopped-motion conditions, the temporal flash-lead effect should be abolished together with the spatial flash-lag effect.

In Experiment 2, we tested this prediction by assessing temporal order judgments and spatial judgments when the flash was presented close to the offset of the moving bar. Deviating from the procedure of Experiment 1, the bar was always completely visible (never fragmented), and participants had to base their temporal order judgments and position judgments on the same event: the stopping of the bar.

In sum, according to the sequential-coding account, we expected that the flash-lead effect in the temporal judgments and the flash-lag effect in the spatial conditions would be eliminated in Experiment 2, because there would be no incentive to prioritize the flash (or the moving object) first and to always encode the position of one particular stimulus first. On the other hand, if the temporal misperception is unrelated to the spatial misperception, there would be no reason to expect that a manipulation that affected (here, eliminated) the spatial misperception should also similarly affect (here, eliminate) the temporal misperception.

Method

Participants A group of 15 new participants took part. All of them did the temporal and the spatial judgment tasks and had normal or corrected-to-normal vision, based on prior testing. Again, 2 participants had to be excluded because their judgments did not vary as a function of the SOA between the flash and the stopping and offset of the bar. The participants were naïve with respect to the experimental hypotheses and gave informed consent.

Apparatus, stimuli, design, and procedure These were identical to those aspects of Experiment 1, except for the following differences: The rotating bar did not change its appearance but instead stopped its motion and vanished at or near the time of the onset and offset of the flash. In the temporal judgment task, the participants judged the onset of the flash relative to the stopping (or offset) of the bar.

Results

The data were treated as described in Experiment 1. Figure 2 (lower panel) depicts the results of the spatial and temporal judgment tasks. There was a small spatial flash-lead effect of 5.32 ms (*SE* = 7.33 ms) in the spatial judgment condition, and also a small temporal flash-lead effect of 4.88 ms (*SE* = 17.81 ms) in the temporal judgment condition. The spatial flash-lead effect was significant, $t(12) = 2.62$, $p = .02$, but the temporal flash-lead effect was not, $t(12) = 0.99$, $p = .34$. Both effects are too small to explain the results of Experiment 1 and are not within the range (or direction) of the typical flash-lag illusion.

Again, we found that the temporal task was more difficult (slope = 40 ms/quartile) than the spatial task (5 ms/quartile). This difference was significant, $t(12) = 3.76$, $p < .01$.

Discussion

According to the sequential-coding explanation, Experiment 1 resulted in a temporal flash-lead effect and a spatial flash-lag effect because the flash served as a temporal marker to start encoding the positions. This encouraged participants first to allocate attention to the flash and encode its position. As a result, encoding of the position of the moving object was delayed, so that it had traveled farther along the trajectory at the time that attention was finally allocated to it, leading to the spatial misperception that the flash was lagging behind the moving object. Both the temporal and spatial illusions were eliminated in Experiment 2 because both the stopping of the motion and the offset (or onset) of the flash could serve equally well as temporal markers to start encoding the positions of flash and moving object. Since there was no systematic preference for first encoding the position of one object over the other, both the temporal and spatial misperceptions were eliminated.

The sequential-encoding explanation certainly constitutes the most parsimonious explanation of the findings of Experiments 1 and 2. However, the findings so far do not necessitate an explanation in terms of preferential encoding: Since the main finding of Experiment 2 was a null effect, it is, for instance, still possible that the differential outcomes were driven by differences in low-level features that were present in Experiment 1 but were eliminated in Experiment 2. Experiment 3 critically tested a low-level explanation against the attentional explanation proposed in the sequential-coding account.

Experiment 3

Experiment 3 provided a critical test of the sequential-coding account, by varying only the incentive to attend first to the flash versus the continuously rotating object, while keeping the low-level visual features identical across all conditions. Hence, if the previous findings of a temporal flash-lead effect and a spatial flash-lag effect were due to differences in the to-be-judged low-level visual features, then we would expect no differences between the temporal and spatial (mis)judgments in Experiment 3. If, on the other hand, the findings of Experiments 1 and 2 were due to sequential coding—here, the fact that the flash was processed with priority versus no priority—and this accounted for the spatial flash-lag effect and the absence thereof, respectively, in the two experiments, then Experiment 3 should show a markedly different result pattern: Specifically, when the stimulus conditions encouraged coding the position of the rotating object first, the flash should be perceived later in time, leading to a reversal of the spatial misperception of a flash-lag effect into a spatial flash-lead effect. If, on the other hand, participants were encouraged to first attend to the flash as the starting signal to begin encoding stimulus positions, the flash should then be perceived first, leading to a delay in the encoding of the rotating object and a spatial flash-lag effect.

This prediction was tested using a jumping (stroboscopically moving) bar as a substitute for the flash. Both the jumping bar and the moving bar travelled on aligned trajectories like the hands of a clock around a virtual hub at the screen center (see Fig. 3, lower right panel). To counterbalance the eccentricities of the stimuli, in Experiment 3a, the rotating bar travelled on the more eccentric trajectory and the flashed or jumping bar on the less eccentric trajectory, while in Experiment 3b, the trajectories were reversed. The rotating bar continuously travelled smoothly with 20 revolutions per minute (1 cycle/3 s). The flashed or jumping bar also revolved 20 times per minute. However, it did so in strobe motion, with an interval of 750 ms between its flashed static presentations at each of the four orthogonal cross-hair positions corresponding to 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock along the trajectories. These will be called the "comparison positions," because they were the only positions where the moving and jumping bars were spatially near enough to be compared to one another.

At the beginning, the jumping and continuously moving bars were shown with a spatial offset, and the participants' task was to adjust the interval between the flashed/jumping

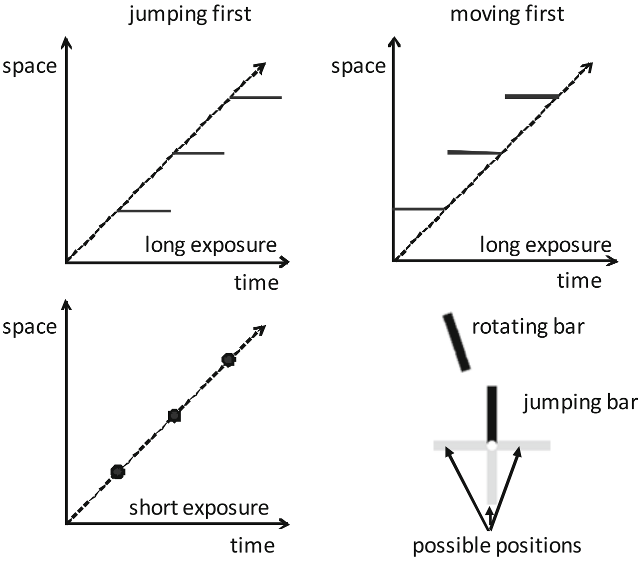


Fig. 3 Space–time plots (upper row and lower left panel) and schematic illustration (lower right panel) of the sequence of events in Experiment 3a. In the "code the jumping bar first" conditions, the jumping bar is only visible at a comparison position when the rotating bar has reached this position (upper left and lower left panels). In the "code the rotating bar first" condition, the order is the other way round (upper right panel): The jumping bar is visible at the comparison positions before the rotating bar has reached these positions. The lower right panel gives a schematic illustration of the stimuli and their sequence. The inner bar (black "jumping bar") jumps from one cross hair to the next (referred to as "possible positions," in gray, in the figure). The outer bar rotates smoothly with 20 rpm on a slightly larger circular trajectory. The task of the participants was to alter the timing between the two stimuli so that both bars would be perceived as exactly aligned at each cross hair (or comparison position) at the moment the inner bar jumped to this position or the outer bar passed this position. In this manner, we manipulated whether our participants would first code the jumping bar or the rotating bar. Participants pressed keys to vary the exact relative timing of the jumping and rotating bars. For further details, refer to the Method section. Experiment 3b was the same, but the eccentricities of the jumping bar and the rotating bar were reversed; that is, the jumping bar was presented in a slightly larger circular trajectory than the rotating bar. The stimuli are not drawn to scale

bar and the rotating bar until the flashed/jumping bar was perceived as being exactly aligned with the rotating bar.

Importantly, in both Experiments 3a and 3b, we manipulated the sequences of coding the two bars. In one blocked condition, the "code the rotating bar first" condition, the jumping bar was presented first at each comparison position and remained there for 750 ms, so that the rotating bar had to "catch up" with the flashed bar. The bars were objectively correctly aligned when their positions matched at the last refresh that the flashed bar was (still) at the comparison position, before it jumped to the next position. Accordingly, participants were instructed to align the interval of the rotating bar so that its position matched the position of the flashed bar directly prior to its offset.

In this condition, attention had to be deployed first to the moving bar, because its arrival was critical for making the required comparison. If, at a comparison position, attention was first deployed to the rotating bar and subsequently to the jumping bar, then perception of the jumping bar would be delayed, so that it would often have arrived at the next position by the time it was perceived. Hence, we would expect a reversal of the spatial misperception—that is, a spatial flash-lead effect—in this condition: Participants should create objectively positive intervals giving the rotating bar a head start over the flashed bar for the two bars to be perceived as aligned.

In the other two, "code the jumping bar first" conditions, the contingencies of the flashed and moving bars were reversed; now, the continuously moving bar preceded the onset of the flashed/jumping bar by almost 1/4th of the trajectory, so that the continuously moving bar arrived first at each comparison position and had almost reached the next comparison position before the offset of the flashed bar. Participants had to adjust the interval of the rotating bar until its position appeared aligned with the onset of the flashed bar at the comparison position: The stimuli were objectively correctly aligned when the position of the rotating stimulus matched the position of the flashed bar at the first refresh that it appeared at the comparison position. In this condition, attention should be deployed to the flashed/jumping bar, because it signals the possibility of making the required comparison, and speeded processing of the position of the flashed bar at its arrival was now critical for the decision.

If the flashed (or jumping) bar was attended first in the "code the jumping bar first" condition, perception of the rotating object should be delayed so that it would be perceived at a position farther along the trajectory. This in turn should result in the typical illusion of a flash-lag effect: To align the perceived locations of flashed and rotating bars at the comparison positions, participants should give the flashed bar a small objective head start over the rotating bar.

In one of the blocked "code the jumping bar first" conditions, we used jumping bars with a flash duration of 750 ms, to render the results compatible with the results of the "code the rotating bar first" condition, and in a second block, we used jumping bars with a flash duration of one frame or 16.6 ms. The latter condition was included as a control, to test whether judgments were biased toward the offset of the 750-ms flashed bar. Such a bias could easily account for the flash-lag effect in the condition in which the flashed bar was visible for an extended duration (e.g., the 750-ms condition) and only its onset position matched the position of the rotating bar. To ensure that the effect observed in the 750-ms condition reflected the classical flash-lag effect and not a bias to skew judgments toward the offset of the flash, the results obtained in the long-presentation condition (750 ms) were compared to the results in the short-presentation condition, in which the bar was flashed only for a single frame. If the results did not differ between the conditions, we could be relatively certain that the judgments were based on the same features, the onsets of the flashed bars, in both presentation conditions of the "code the jumping bar first" condition.

Our manipulation proved to be so strong that it could easily be seen by virtually everyone (see http://ppcms.univie.ac.at/fileadmin/usermounts/priessh9/jumpingDemo.html).

Method

Participants of Experiments 3a and 3b Because everybody could see the illusion in our Web demo, only 5 voluntary observers, including the first author (H.-W.P.), were tested for an illustration of the effect. All had normal or corrected-to-normal vision, based on prior testing. Again, all gave informed consent.

Apparatus of Experiments 3a and 3b A PC with a 21-in. color monitor (Eizo Flexscan T 962) and a resolution of 1,024 × 768 pixels controlled the timing of the events and generated the stimuli. Event scheduling and response measurement were controlled by MATLAB and the Psychophysics Toolbox (Brainard, 1997). Control of gaze direction at the center of the screen was secured with an SMI RED-II eyetracker.

Stimuli of Experiment 3a See also Fig. 3. The stimuli were white bars (94 cd/m^2) on a dark gray (4 cd/m^2) background. The viewing distance was 83 cm. Both bars had a length of 1.62º and a width of 0.27º circling around (and pointing toward) screen center. The jumping bar was presented on a less eccentric trajectory and the rotating bar was shown on a more eccentric trajectory: The jumping bar's less eccentrically presented end was centered on the screen, whereas the rotating bar's less eccentrically presented end was shown with a 2.16º distance from the screen center. Thus, there was a 0.54º-wide gap between the more eccentric end of the aligned jumping bar and the less eccentric end of the rotating bar. Both bars travelled clockwise around the screen center with a speed of 20 cycles per minute. The rotating bar moved smoothly across the screen: It was shown at adjacent positions on its motion trajectory, with an SOA of 16.6 ms and an interstimulus interval (ISI) of 0 ms between its successive presentations. In different blocks of the "code the jumping bar first" condition, the jumping bar was presented for either 750 ms (with an ISI of 0 ms) or flashed for 16.6 ms (i.e., one refresh of the computer screen) and an SOA of 750 ms at the four comparison positions on its motion trajectory—at the 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock positions. In the "code the jumping bar first" conditions, the rotating bar was almost at a comparison position when the jumping bar caught up with the rotating bar to complete the pair of bars at a comparison position. In a final, blocked "code the rotating bar first" condition, the jumping bar was always presented first at a comparison position (for a duration of 750 ms in total), and the rotating bar completed the pair of bars at this position.

Stimuli of Experiment 3b Everything was exactly the same as in Experiment 3a, but the rotating bar was shown on the less eccentric trajectory and the jumping bar was shown on the more eccentric trajectory. (Our expectations were the same as in Exp. 3a. If the same results were observed in Exps. 3a and 3b, we could rule out that eccentricity differences accounted for the expected results.)

Procedure of Experiments 3a and 3b A block started with a nine-point eyetracker calibration. If a participant failed to fixate on the center of the screen during a trial, the trial was discarded and repeated at a later point of the experiment. Each of the two "code the jumping bar first" conditions (with 750-ms and with 16.6-ms durations of the jumping bar, respectively) and the "code the rotating bar first" condition were presented in separate blocks. Block order varied randomly between participants. In the "code the jumping bar first" conditions, participants had to wait for the jumping bar to complete a pair of bars for a judgment of the bars' alignment, and in the "code the rotating bar first" condition, participants had to wait for the rotating bar until they could judge the bars' relative positions.

Each block started with an instruction for the following task and three warm-up trials, during which fixation was successfully held at screen center and the temporal interval was adjusted. After the warm-up, the answers from 16 trials per condition were recorded for analysis. At the outset of each trial, the two bars were presented with a temporal asynchrony of 1/4 revolution at the comparison positions, and the participant's task was to adjust the interval between the two bars so that the rotating and jumping bars were perceived as aligned at the comparison positions. In all conditions, participants pressed a right key to increase the temporal interval between the two moving bars and the left key to reduce the temporal interval. After perceiving both bars aligned at the comparison positions, the participant pressed the space bar to confirm that he or she saw the bars as aligned, and the next trial began with the rotating bar either temporally leading or lagging the jumping bar.

Participants were not instructed to explicitly code either the jumping/flashed bar or the rotating bar first. Instead, the different orders of sequential coding were suggested by the way that the stimuli were presented to the participants, with either the jumping bar or the rotating bar completing the pair of stimuli at a comparison position.

Eye movement control in Experiments 3a and 3b Sometimes spatial illusions, such as the flash-lag effect, can be altered by and confounded with eye movements. This does not seem to be the case with the present procedure (compare with the Web demo), but as a security measure, we recorded eye movements. Trials on which the measured gaze position deviated by more than 0.81° from the center of the fixation point were discarded and later repeated.

Results

Results of Experiment 3a Spatial misperception was inferred from the participants' created (or selected) objective temporal intervals between the two bars (the rotating and jumping bars) for their perception of spatial alignment of the two bars. For the results, see also Fig. 4.

As expected, in the "code the jumping bar first" conditions, a spatial flash-lag effect was found, and participants had to compensate for the delayed perception of the rotating bar, so that the mean intervals were negative. With the long presentation of the flashed bar (750 ms), participants created a mean interval of −85.93 ms (*SD* = 33.75 ms; within-participants *SD* [SD_{within}] = 33.48 ms), and in the short-presentation condition (16.6 ms), they created an interval of −51.08 ms (*SD* = 17.42 ms; SD_{within} = 22.56 ms). This means that in the "code the jumping bar first" conditions, the rotating bar had to be presented at least 51 ms prior to the jumping or flashed bar at the comparison positions for the participants to perceive both bars as aligned at these positions.

By contrast, in the "code the rotating bar first" condition, the mean interval was 50.23 ms (*SD* = 21.33 ms; SD_{within} = 31.43 ms). This means that, as expected, the jumping bar had to be presented 50 ms before the moving bar at the comparison positions for the participants to perceive the two moving bars as spatially aligned at these positions.

Results of Experiment 3b Experiment 3b replicated these results. In the long-presentation condition (750 ms) of the "code the jumping bar first" condition, the rotating bar had to precede the jumping bar by an interval of −66 ms (*SD* = 19.33 ms; SD_{within} = 22.65 ms), and with the short presentation duration (16.6 ms), the rotating bar had to precede the jumping or flashed bar by −54.33 ms (*SD* = 14.08 ms; SD_{within} = 19.39 ms) for the two bars to be perceived as spatially aligned at the comparison positions.

By contrast, in the "code the rotating bar first" condition, the jumping or flashed bar had to precede the rotating bar by 13.95 ms (*SD* = 17.17 ms; SD_{within} = 40.18 ms).

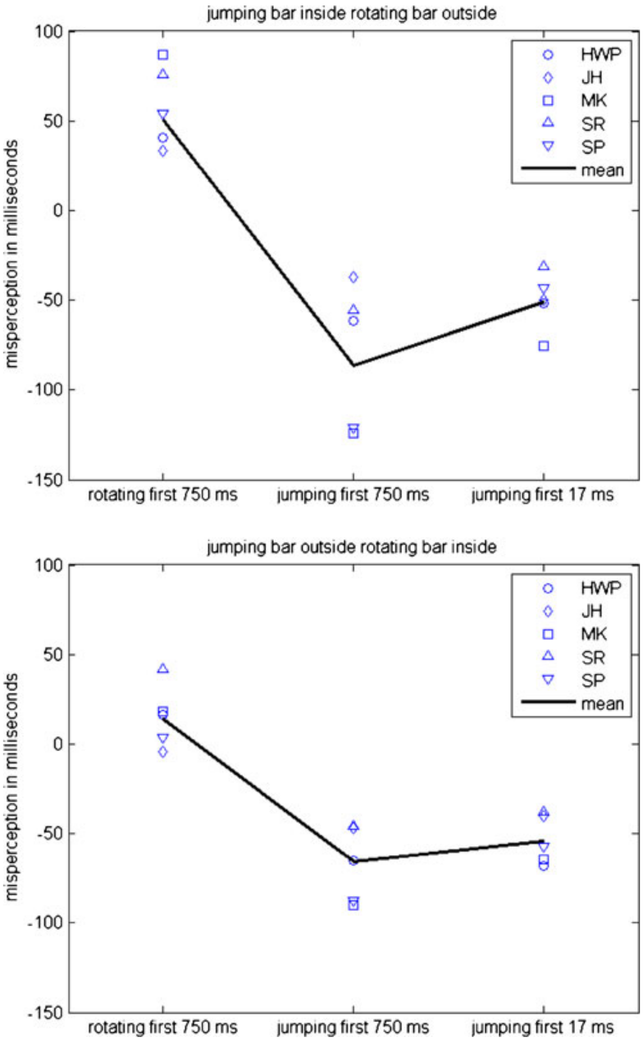


Fig. 4 Participants' average created intervals between the jumping bar and the rotating bar for their perception of both bars as aligned. Individual values represent the mean values of 16 measurements. The black line shows the mean values of all 5 observers. (Upper panel) Results of Experiment 3a. In the "code the jumping bar (750 ms) first" condition, the rotating bar had to precede the jumping bar by an average of 86 ms to be perceived as aligned with the jumping bar. This means that the rotating bar was perceived with a delay of 86 ms. Correspondingly, in the "code the jumping bar (16.6 ms) first" condition, the rotating bar was perceived with a delay of 51 ms. By contrast, in the "code the rotating bar first" condition, the jumping bar rather than the rotating bar was perceived with a delay of 50 ms. (Lower panel) Results of Experiment 3b. In the "code the jumping bar (750 ms) first" condition, the rotating bar was perceived with a delay of 66 ms. In the "code the jumping bar (16.6 ms) first" condition, the rotating bar was perceived with a delay of 54 ms. By contrast, in the "code the rotating bar first" condition, the jumping bar was perceived with a delay of 14 ms

Discussion

Experiment 3 showed that sequentially coding two different bars, one rotating and one flashing, in turn can cause a spatial misperception of the relative location of the rotating bar. This was evident from the fact that we were able to manipulate the direction of the spatial misperception by forcing the participants to code first either the flashed/jumping bar or the rotating bar at a particular position. If the participants coded the rotating bar first and then the flashed/jumping bar, a reversed spatial misperception to the typical flash-lag effect, a spatial flash-lead effect, was observed. Only if the participants coded the flashed/jumping bar first and then the rotating bar was the rotating bar seen as shifted in the direction of its motion. These spatial misperceptions are almost certainly a consequence of differences in the orders in which the bars were sequentially attended.

The different judgment conditions were absolutely identical in terms of their low-level features. This rules out any alternative explanation of the spatial misperception in terms of other latency differences, such as in the processing of the bars' visual low-level features. In line with this conclusion, the few low-level features that discriminated between the two stimuli to be compared in the present experiment, such as their exact eccentricity, their continuity of motion, and their overall duration affected the size of the misperception, but not its direction. The direction of the misperception effect—that is, whether a negative or positive interval was created for the participants' perception of spatial alignment—was governed solely by the sequence of coding the two bars. By exclusion of the alternative explanations in terms of sensory differences as the responsible factors for the sequence of coding the bars, the results thus supported the assumption that the sequence of first attending to one stimulus and then the other must have created the spatial misperception.

This interpretation could be criticized on grounds that the task differed between the two conditions. Participants had to align the position of the rotating bar with the jumping bar just prior to its offset in the "code the rotating bar first" condition, whereas they had to align it with the jumping bar's first refresh (or onset) at a comparison position in the "code the jumping bar first" condition. It might thus seem that the different results could be due to the stronger or weaker potential of the jumping bar to capture attention, because past research has seemingly demonstrated a unique role of onsets for capturing attention in a stimulus-driven way (cf. Yantis & Jonides, 1984). This, however, is unlikely. First of all, subsequent studies have shown that offsets have a strong potential to capture attention, too: If the onsets are task-relevant, they capture attention, and if the offsets are task-relevant, they capture attention instead (Atchley, Kramer, & Hillstrom, 2000). Secondly, in line with this flexibility of attentional control (and more to the point), Baldo, Kihara, Namba, and Klein (2002) tested the flash-lag effect in response to a flash of a duration of a single refresh and in response to a stationary object's onsets and offsets, and they found a flash-lag effect across all three conditions, with an even larger flash-lag effect in the offset condition. These results demonstrate that the effects were not due to the difference of aligning the onset versus offset with the position of the rotating bar.[1]

However, one observation in Experiment 3 was not expected: The spatial misperception in the "code the rotating bar first" condition was stronger in the conditions in which the rotating bar was at a more eccentric position on the screen. If the rotating bar was presented less eccentrically, the necessary interval to compensate for the earlier coding of the rotating bar was significantly smaller (13 ms) than when the rotating bar was presented more eccentrically (50 ms), $t(4) = 4.06$, $p = .02$. Two possible explanations can conceivably account for this difference: First, it is possible that this effect was due to metacontrast masking, which has been reported to be weaker for less eccentric positions and increases with more eccentric stimulus positions (cf. Bridgeman & Leff, 1979). More effective masking of preceding stimulus positions by subsequent stimulus positions on the motion trajectory is known to contribute to the misperception of moving stimuli (cf. Kirschfeld & Kammer, 1999) and would have further delayed perception of the position of the moving object, increasing the illusion of a spatial offset. Second, it is possible that the flash-lag effect was reduced because the moving bar had a lower tangential velocity when it was presented nearer to the screen center, and correspondingly, may have appeared less displaced (Nijhawan, 1994).

General discussion

In the first experiment, we showed that a spatial misperception, such as the flash-lag effect, co-occurs with a temporal misperception. Experiment 1 revealed that, in the typical stimulus conditions of a flash-lag effect, our participants perceived a flash as temporally preceding a concomitant change of a continuously rotating bar when the

---

[1] The findings of Baldo et al. (2002) are also consistent with the present findings, since participants in the previous study were not instructed to attend to the moving object, but presumably attended first to the offset. Moreover, in Baldo et al.'s study, the offsetting bar did not reappear at a future position of the trajectory, as was the case in the present study, so there was no chance that delayed perception of the jumping bar would result in the perception of the flash leading the object. Hence, the present findings can be safely attributed to the differences in the orders in which objects were sequentially coded or attended.

rotating bar was perceived to be spatially shifted in the direction of its motion. These results are in line with the assumption that sequential coding of flash and moving stimuli, such as in an attentional account, could be responsible for the spatial misperception. According to an attentional account, for example, the flash is usually attended first because it is presented only very briefly and thus signals task onset. This leads to its coding before that of the moving stimulus at or near its position. As a consequence, perception of the moving stimulus is delayed so that it is seen shifted in its motion direction, either because the earlier flash serves as an onset signal for an integrated perception of the moving stimulus over a few successive frames (cf. Eagleman & Sejnowski, 2000b) or because deploying attention to the flash facilitates perception of the flash but delays perception of the moving stimulus (cf. Baldo & Klein, 1995).

In the second experiment, we demonstrated that the temporal and spatial misperceptions not only co-occur but can be jointly manipulated in a predictable manner. Both of the misperception effects vanished when the stimulus conditions did not favor only one particular sequence of coding the two stimuli. In this condition, the flash and the rotating bar were presumably coded either simultaneously or sequentially, where the order of coding randomly varied between trials. The fact that the flash lag disappeared alongside the temporal misperception suggests that the flash-lag effect could indeed be due to sequential coding of the flash and the rotating bar. The corresponding preference for one type of sequential coding disappears when there is no clear incentive to code the position of only one stimulus prior to the other.

In the third experiment, we showed that the position of a rotating stimulus can be perceived as lagging or leading a jumping (or flashed) bar when in fact the two stimuli are objectively spatially aligned. Experiment 3 revealed that the sequence of coding the flashing versus the rotating bar was critical for the direction of the misperception (i.e., spatial flash-lag effect or spatial flash-lead effect, respectively). When the jumping bar was presented first at each comparison position and the rotating bar had to catch up with it, the movement of the rotating bar towards the comparison position was critical for the task, and therefore attention was mainly allocated to the rotating bar. In this condition, coding the rotating bar first delayed perception of the jumping bar, resulting in a spatial flash-lead effect. When the rotating bar was presented first at the comparison positions and the jumping bar had to catch up with it, the jumping bar was the critical stimulus and, hence, was first and foremost attended. Sequential coding of the jumping bar first and of the rotating bar afterward delayed perception of the rotating bar, creating a spatial flash-lag effect.

The present study is therefore in line with the explanation of the spatial misperception in terms of a sequence of coding first the flash and then the rotating bar—for example, by prior entry of an attended flash and a concomitant delay of the perception of a rotating stimulus, or in the form of an onset signal provided by the first-attended-to flash for the integration of visual information from the rotating stimulus and just after the onset of the flash. However, we cannot tell whether attention caused the spatial misperception by serving as a point of reference for the start of the integration of visual information from the moving bar over a few successive displays, or by being a necessary precondition for the perception of the moving bar. The present experiments do not allow us to distinguish between these two alternative explanations.

For a long time, it has been claimed that the sequential coding of stimuli based on a sequence of attending first to one and then to another stimulus, position, or feature could be responsible for the participant's percept of visuospatial input (cf. Titchener, 1908; see also Neumann & Niepel, 2004; Scharlau, 2002; Scharlau & Ansorge, 2003; Scharlau, Ansorge, & Horstmann, 2006). However, it has proven difficult to show that the sequence of sequential coding by successive attentional focusing could be responsible for spatial (mis)perceptions. The results of the present study clearly demonstrate that spatial misperceptions can arise from differences in allocating attention alone, and thus confirm earlier attentional explanations of diverse visual illusions (cf. Baldo et al., 2002; Baldo & Klein, 1995; Chappell, Hine, Acworth, & Hardwick, 2006; Müsseler & Aschersleben, 1998).

Specifically, it could be argued that previous results can partly be explained by reference to processing latencies between confounded low-level visual features (cf. Kirschfeld & Kammer, 1999; Nijhawan, 1994; Nijhawan, Watanabe, Khurana, & Shimojo, 2004; Öğmen, Patel, Bedell, & Camuz, 2004; Purushothaman et al., 1998). The same could be said, for example, of the first two experiments of the present study. Although, together, Experiments 1 and 2 were also suggestive of a contribution of sequentially focusing attention to a spatial misperception, such as the flash-lag effect, we noted that there were also subtle sensory feature differences between the flash and the rotating stimulus (which are typical of flash-lag experiments), and these may have contributed to the observed effects. For example, the contrast signs of the flash (white) and of the rotating stimulus (black) were different, and the flash always consisted of temporally proximal on- and offsets, but the moving stimulus change consisted of only an on- or offset at a particular point in time. Previous studies have indicated that such differences can contribute to spatial misperceptions, such as the flash-lag effect (cf. Gauch & Kerzel, 2009; Sheth, Nijhawan, & Shimojo, 2000; Whitney, Murakami, & Cavanagh, 2000). In fact, we accidentally confirmed one of these perceptual factors, eccentricity, as an additional contributor to the percept in the "code the rotating stimulus first" conditions of Experiment 3 (e.g., Baldo et al., 2002; Kirschfeld & Kammer, 1999).

Such confounding low-level feature differences, however, were absent in the present Experiment 3, because the experimental conditions differed only in the order in which the stimuli arrived at a particular comparison position, whereas all of the low-level features were either identical or balanced across Experiments 3a and 3b. Thus, the large spatial misperceptions in Experiment 3 were undoubtedly caused by the sequence of coding first the jumping or the rotating stimulus. These results indicate that differences in the deployment of attention may also play a more important role in visual illusions than is currently appreciated.

Author note We thank Mike Dodd and one anonymous reviewer for excellent comments on a previous version of the present article. The research was supported by Deutsche Forschungsgemeinschaft Grants Scha 1515/1-1, to I.S. and U.A., and AN 393/2-1, to U.A.

References

Ansorge, U., Carbone, E., Becker, S. I., & Turatto, M. (2010). Attentional capture by motion onsets is spatially imprecise. *European Journal of Cognitive Psychology, 22,* 62–105. doi:10.1080/09541440902733190

Atchley, P., Kramer, A. F., & Hillstrom, A. P. (2000). Contingent capture for onsets and offsets: Attentional set for perceptual transients. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 594–606. doi:10.1037/0096-1523.26.2.594

Baldo, M. V. C., Kihara, A. H., Namba, J., & Klein, S. A. (2002). Evidence for an attentional component of the perceptual misalignment between moving and flashing stimuli. *Perception, 31,* 17–30. doi:10.1068/p3302

Baldo, M. V. C., & Klein, S. A. (1995). Extrapolation or attention shift? *Nature, 378,* 565–566.

Bashinski, H. S., & Bacharach, V. R. (1980). Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations. *Perception & Psychophysics, 28,* 241–248.

Becker, S. I., Ansorge, U., & Turatto, M. (2009). Saccades reveal that allocentric coding of the moving object causes mislocalization in the flash-lag effect. *Attention, Perception, & Psychophysics, 71,* 1313–1324. doi:10.3758/APP.71.6.1313

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 433–436. doi:10.1163/156856897X00357

Breitmeyer, B. G., & Ogmen, H. (2006). *Visual masking: Time slices through conscious and unconscious vision*. Oxford: Oxford University Press.

Bridgeman, B., & Leff, S. (1979). Interaction of stimulus size and retinal eccentricity in metacontrast masking. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 101–109.

Carbone, E., & Ansorge, U. (2008). Investigating the contribution of metacontrast to the Fröhlich effect for size. *Acta Psychologica, 128,* 361–367. doi:10.1016/j.actpsy.2008.03.008

Chappell, M., Hine, T. J., Acworth, C., & Hardwick, D. R. (2006). Attention "capture" by the flash-lag flash. *Vision Research, 46,* 3205–3213.

Dunlap, K. (1910). The complication experiment and related phenomena. *Psychological Review, 17,* 157–191. doi:10.1037/h0073064

Eagleman, D. M., & Sejnowski, T. J. (2000a). Flash-lag effect: Differential latency, not postdiction. Response to Patel et al., *Science*, *290*, 1051a.

Eagleman, D. M., & Sejnowski, T. J. (2000b). Motion integration and postdiction in visual awareness. *Science, 287,* 2036–2038. doi:10.1126/science.287.5460.2036

Eagleman, D. M., & Sejnowski, T. J. (2007). Motion signals bias localization judgments: A unified explanation for the flash-lag, flash-drag, flash-jump, and Frohlich effects. *Journal of Vision*, *7* (4), 3:1–12. doi:10.1167/7.4.3

Enns, J. T., Brehaut, J. C., & Shore, D. I. (1999). The duration of a brief event in the mind's eye. *The Journal of General Psychology, 126,* 355–372.

Fröhlich, F. W. (1929). *Die Empfindungszeit—Ein Beitrag zur Lehre von der Zeit-, Raum- und Bewegungsempfindung [The sensation time—a contribution to the lore of time, space and motion sensation]*. Jena, Germany: Gustav Fischer.

Gauch, A., & Kerzel, D. (2009). Contributions of visible persistence and perceptual set to the flash-lag effect: Focusing on flash onset abolishes the illusion. *Vision Research, 49,* 2983–2991. doi:10.1016/j.visres.2009.09.018

Kerzel, D. (2010). The Fröhlich effect: Historical notes and relation to the flash-lag, current theories and reconciliation with the onset repulsion effect. In R. Nijhawan & B. Khurana (Eds.), *Space and time in perception and action* (pp. 321–337). Cambridge: Cambridge University Press.

Kirschfeld, K., & Kammer, T. (1999). The Fröhlich effect: A consequence of the interaction of visual focal attention and metacontrast. *Vision Research, 39,* 3702–3709.

Mattes, S., & Ulrich, R. (1998). Directed attention prolongs the perceived duration of a brief stimulus. *Perception & Psychophysics, 60,* 1305–1317. doi:10.3758/BF03207993

Müsseler, J., & Aschersleben, G. (1998). Localizing the first position of a moving stimulus: The Fröhlich effect and an attention-shifting explanation. *Perception & Psychophysics, 60,* 683–695. doi:10.3758/BF03206055

Müsseler, J., & Neumann, O. (1992). Apparent distance reduction with moving stimuli (tandem effect): Evidence for an attention-shifting model. *Psychological Research, 54,* 246–266.

Müsseler, J., Stork, S., & Kerzel, D. (2008). Localising the onset of moving stimuli with a pointing task and a relative judgment task. *Vision Research, 48,* 611–617.

Neumann, O., & Niepel, M. (2004). Timing of perception and perception of time. In C. Kaernbach, E. Schröger, & H. Müller (Eds.), *Psychophysics beyond sensation* (pp. 245–279). Mahwah, NJ: Erlbaum.

Nijhawan, R. (1994). Motion extrapolation in catching. *Nature, 370,* 256–257.

Nijhawan, R., Watanabe, K., Khurana, B., & Shimojo, S. (2004). Compensation of neural delays in visual–motor behaviour: No evidence for shorter afferent delays for visual motion. *Visual Cognition, 1,* 275–298.

Öğmen, H., Patel, S. S., Bedell, H. E., & Camuz, K. (2004). Differential latencies and the dynamics of the position computation process for moving targets, assessed with the flash-lag effect. *Vision Research, 44,* 2109–2128. doi:10.1016/j.visres.2004.04.003

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3–25. doi:10.1080/00335558008248231

Priess, H.-W. (2011). Personal CMS: Home [Sofware demo]. Retrieved April 13, 2011, from http://ppcms.univie.ac.at/fileadmin/usermounts/priessh9/jumpingDemo.html

Purushothaman, G., Patel, S. S., Bedell, H. E., & Ogmen, H. (1998). Moving ahead through differential visual latency. *Nature, 396,* 424. doi:10.1038/24766

Rizzolatti, G., Riggio, L., Dascola, I., & Umiltà, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of premotor theory of attention. *Neuropsychologia, 25,* 31–40. doi:10.1016/0028-3932(87)90041-8

Scharlau, I. (2002). Leading, but not trailing, primes influence temporal order perception: Further evidence for an attentional account of perceptual latency priming. *Perception & Psychophysics, 64,* 1346–1360.

Scharlau, I., & Ansorge, U. (2003). Direct parameter specification of an attention shift: Evidence from perceptual latency priming. *Vision Research, 43,* 1351–1363. doi:10.1016/S0042-6989(03)00141-X

Scharlau, I., Ansorge, U., & Horstmann, G. (2006). Latency facilitation in temporal-order judgments: Time course of facilitation as a function of judgment type. *Acta Psychologica, 122,* 129–159. doi:10.1016/j.actpsy.2005.10.006

Sheth, B. R., Nijhawan, R., & Shimojo, S. (2000). Changing objects lead briefly flashed ones. *Nature Neuroscience, 3,* 489–495. doi:10.1038/74865

Shore, D. I., Spence, C., & Klein, R. M. (2001). Visual prior entry. *Psychological Science, 12,* 205–212. doi:10.1111/1467-9280.00337

Stelmach, L. B., & Herdman, C. M. (1991). Directed attention and perception of temporal order. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 539–550. doi:10.1037/0096-1523.17.2.539

Titchener, E. M. (1908). *Lectures on the elementary psychology of feeling and attention*. New York: Macmillan.

von Helmholtz, H. (1894). Über den Ursprung der richtigen Deutung unserer Sinneseindrücke [About the origin of the correct interpretation of our sensory impressions]. *Wissenschaftliche Abhandlungen, Dritter Band* [Scientific proceedings, third volume]. Leipzig, Germany: Barth.

Whitney, D., Murakami, I., & Cavanagh, P. (2000). Illusory spatial offset of a flash relative to a moving stimulus is caused by differential latencies for moving and flashed stimuli. *Vision Research, 40,* 137–149.

Wichmann, F. A., & Hill, N. J. (2001). The psychometric function: I. Fitting, sampling and goodness-of-fit. *Perception & Psychophysics, 63,* 1293–1313.

Wundt, W. (1896). *Grundriß der Psychologie [Compendium of psychology]*. Leipzig, Germany: Engelmann.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 601–621. doi:10.1037/0096-1523.10.5.601