Confusion of space and time in the flash-lag effect

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Abstract. The apparent lagging of a short flash in the relation to a moving object, the flash-lag effect (FLE), has so far been measured mainly in terms of illusory spatial offset. We propose a method of measuring the perceived temporal asynchrony of the FLE separately from its perceived spatial offset. We presented a moving stimulus that changed its colour at a certain moment. The observer indicated, in two different tasks, where and when the colour change occurred in relation to a stationary reference flash. Results show that the perceived time of the colour change was not congruent with the perceived location of the colour change: the colour change is perceived simultaneously with the flash, but is shifted in position. The presentation of the reference in the form of a flash is not critical for the occurrence of the FLE, because the same effect was obtained with a constantly visible reference signal, the position of which or time when it changed its colour were varied. The observer was not able to ignore the irrelevant dimension of the reference signal: the apparent time of the colour change was influenced by the position of the reference signal, and the apparent location of the colour change was influenced by the presentation time of the reference signal. The observer’s inability to separate the spatial and temporal aspects of the moving stimulus clearly imposes certain limits on theories that are attempting to explain the FLE exclusively in terms of the perceived space and time.

1 Introduction
In 1861 Wilhelm Wundt constructed a simple pendulum that swung across a scale and caused a spring to give a click at a given point in its excursion (Boring 1957, page 146). It was von Tchisch, however, who found several conditions that altered the apparent coincidence of the perceived visual and acoustic events. A student of Wundt and Emil Kraepelin’s successor on his Dorpat (now Tartu) Chair of Psychiatry, he noticed that in some cases a click appeared to sound before the pendulum actually reached the spring; in other cases it appeared to sound later when the pendulum had already passed the spring (von Tchisch 1885). Since then, the apparent lagging behind of a moving object in relation to a short sound or flash was repeatedly rediscovered and has recently become known under the name of the flash-lag effect (FLE—Nijhawan 1994). To measure the FLE, the observer usually adjusts the spatial position of the flash in relation to a moving object. The spatial offset that is required to make the moving object coincident with the flash is regarded as the measure of the FLE. This spatial lag is often believed to be a direct indicator of the perceived momentary position of the moving object (Nijhawan 1994, 1997; Khurana and Nijhawan 1995). According to another popular interpretation, the apparent spatial offset corresponds to a perceptual delay that can be found by the division of the spatial offset by the velocity of the moving object (eg Baldo and Klein 1995; Whitney and Murakami 1998; Whitney et al 2000).

The determination of temporal order of two identical visual events appears to be trivial—it is simply necessary to determine their succession. A minor complication arises from the fact that the succession may form a new type of event, like movement, that can considerably improve the resolution ability (Exner 1875; Allik and Kreegipuu 1998). The situation becomes even more complicated when events are not completely identical (Allik and Pulver 1994). There is no simple and transparent rule for predicting
the apparent perceptual order of two arbitrary luminance excursions of which, for
instance, one is translating the pattern of luminance flux across the retina and the
second is a stationary flash. In order to be perceived, both events need to be trans-
formed into two different internal representations. Only on the basis of these internal
representations, that are intrinsically noisy and may take a different time to develop,
can the observer make a decision about the temporal order in which these two events
were presented (cf Allik and Pulver 1994; Murakami 2001).

So far the magnitude of the FLE has mainly been measured in terms of illusory
spatial offset between a momentary position of a moving stimulus and a stationary
flash. In order to align the probe flash with the passing moving stimulus, the flash needs
to be shifted forward, towards the movement direction, to a position that the moving
object has not yet reached. However, this is not the same as measuring the perceived
synchrony of two events. When researchers have speculated about differential percep-
tual delays, they have inferred these delays from the illusory spatial offset, calculating
how much time it would take for a moving stimulus to cover the distance equal to
this apparent spatial lag (but see Eagleman and Sejnowski 2000a, 2000b, 2002 for
the few exceptions). We find this practice questionable because the perceived momen-
tary position may not correspond to the equivalent subjective time moment. It is
even possible, at least theoretically, that despite considerable spatial misperception,
both objects are perceived perfectly simultaneously (Eagleman and Sejnowski 2000a,
2000b, 2002).

In this study we are presenting an idea how to measure the perceived temporal
offset of the FLE separately from its perceived spatial offset. The idea is simple and
inspired by colour-changing stimulus used by Moutoussis and Zeki (1997). Instead of
comparing the momentary position of a moving stimulus with a stationary flash, we
presented a moving stimulus which at a certain moment (the switch point) changed its
colour: a green moving bar, for example, becomes instantly red while continuing
its previous motion. The moment of change can be estimated in two different ways.
First, the observer’s task can be to determine the spatial location of the change by
judging whether the change of colour happened before or after the moving stimulus
passed the adjacent stationary reference flash. Second, the observer can determine the
time of the change by judging whether the colour change occurred before or after
the onset of the reference flash. In this way it is possible to obtain separate estimates
of both the spatial and temporal offset. For instance, Cai and Schlag (2001) who
were, according to our knowledge, the first to use this experimental idea, discovered
that when the moving stimulus changes colour simultaneously with the flash, the
colour change is perceived simultaneously with the flash but shifted in position. Thus,
if their results are confirmed, we are potentially facing a paradoxical situation that
the perceived time moment of colour change is not identical to the spatial position
where this colour change appears to take place. Although it seems counterintuitive
that internal representations of spatial and temporal aspects of a moving stimulus are
not congruent, it is still possible that these two fundamental aspects have their own
distinctive representations, and it is not possible to deduce the perceived time from
the apparent location or vice versa (cf Eagleman and Sejnowski 2002; Kreegipuu and
Allik 2003).

One reason for the incongruency between spatial and temporal judgments may be
confusion of space and time—these two physical attributes are not clearly separated
in the internal representation of motion. So far, the analysis of the FLE has been
based on the particular assumption that the human observer is able to separate one
simple aspect, momentary spatial position, of a complex stimulus and compare it with
the same attribute abstracted from another stimulus. There is no doubt that the observer
is able to separate out one single aspect of the stimulus. What is doubtful, however,
is whether or not this abstracted attribute coincides with the attribute manipulated by the experimenter (Allik 1989). The whole history of visual science demonstrates the observer’s inability to abstract dimensions, including space and time, manipulated by the experimenter from all other stimulus attributes. It is a well-known regularity that temporal judgments depend on spatial configuration of the stimulus and vice versa. Helson was probably the first to notice the tau effect: the perceived spatial distance is influenced by the temporal interval between two stimuli that mark this spatial distance even though the observer has been instructed to ignore the latter (Helson and King 1931). In turn, the kappa effect is the change of the perceived time interval as a function of spatial separation between signals indicating the beginning and the end of the time interval (eg Abe 1935; Cohen et al 1953). In both situations, the observer is unable to ignore the irrelevant aspect of the stimulus confusing time with space or space with time. As was demonstrated by Collyer (1977), these two effects, kappa and tau, are only partly symmetrical.

Most researchers seem to believe that the FLE originates from the differences in the processing of moving and flashing stimuli. For example, a hypothesis has been put forward that the FLE occurs simply because the visual system processes moving stimuli faster than stationary flashes (eg Whitney and Murakami 1998). However, it is unclear specifically what is compared when the momentary position of the moving stimulus is matched to the onset of the stationary flash. Was the perceptual delay caused by differences in the processing of the moving object and the same object when it stayed stationary, or was it due to differences in the perception of the first appearance of the object and the detection of the displacement of the same object when it was already permanently visible? In order to disentangle confounding stimulus attributes, it is necessary to make the compared visual events identical except for a single critical attribute. For example, when we are interested in the effect of motion, separately from the effects caused by a sudden appearance of the stimulus in the visual field, we need to compare the object moving in the frontoparallel plane with the same object when it remains in the same spatial position. There are many demonstrations that a moving object looks different from its stationary appearance. Visual deformation of moving objects can be attributed to visual mechanisms, such as spatiotemporal summation and visual masking, that transform the distribution of colour and brightness in visual space (cf Dzhafarov 1992a). Beside these deformations, however, the metric of the visual space itself changes in visual motion (Dzhafarov 1992b). For example, the perceived spatial distances between visual objects moving with the same velocity shrink along the direction of motion (Dzhafarov 1992c). To test whether the FLE is a kinematic effect or not we presented two identical bars one of which was moving with constant velocity and the other was stationary. At two independent moments of time they both changed their colour. The observer’s task was to estimate whether the perceived colour changes occurred simultaneously or not. If the perceived simultaneity of these two colour changes are shifted, this can be solely attributed to kinematic effects, the transformation of spatiotemporal coordinates of visual objects in visual motion.

This study, consequently, had three aims. First, to measure spatial and temporal lags of the FLE separately, and to determine whether the perceived time and location of the colour change are congruent or not. Second, we were interested in the question how well the observer is able to separate spatial and temporal aspects of the stimulus that are typical to the FLE experiments. Third, we made an attempt to disentangle confounding stimulus attribute and test if it is possible to find the apparent spatial or temporal lag without using a reference flash.
2 Experiment 1

2.1 Method

2.1.1 Observers. Four subjects, one male and three female (aged from 19 to 28 years), took part in the experiment. They all had normal or corrected-to-normal vision. Two observers were naive with respect to the experimental design and goals. One participant (an author of this study) had extensive practice in psychophysical experiments; for the three others the experiment was their first one.

2.1.2 Apparatus and stimuli. Stimuli were generated on the screen of a 19-inch Hewlett Packard monitor (23.11 deg x 14.94 deg) with the aid of Cambridge Research Systems VSG 2/3. The frame rate was 200 Hz. Observers sat at a 90 cm viewing distance from the screen, fixating a small cross (0.25 deg x 0.64 deg) in the centre of the screen. The background luminance of the screen was 5.5 cd m$^{-2}$. A schematic view of stimulus configuration is presented in figure 1.

![Figure 1](image-url)  
Figure 1. A schematic view of the stimulus configuration. A 1.91 deg by 0.25 deg moving bar (T), either red or green, appeared on the border of the screen and started to move across the screen with one of two constant velocities (6.4 deg s$^{-1}$ or 25.6 deg s$^{-1}$). In the middle third of the trajectory at the moment ($s_T$, $t_T$) the T changed its colour. The position ($s_R$, $t_R$) of an achromatic reference (R) flash was adjacent to the place and time of the colour change. The observer’s task was to adjust the onset time $t_R$ of the R (temporal judgment) or its spatial position $s_R$ (spatial judgment) so that it coincided with the colour change. The situation in the graph corresponds to negative $\Delta t$ and positive $\Delta s$.

A green or red rectangular test (T) bar with the size of 0.25 deg x 1.91 deg and with a luminance of 11.2 cd m$^{-2}$ appeared at the left or right edge of the screen and started to move horizontally across the screen with one of two constant velocities, 6.4 deg s$^{-1}$ or 25.6 deg s$^{-1}$, depending on the experimental series. At some randomly determined moment of time $t_T$ and position $s_T$ in the middle third of its trajectory (the 'switch point') the moving stimulus changed its colour from green to red or from red to green. There were two different series of experiments depending on the task. In the first of these tasks, *time judgment*, the observer was asked to judge whether the colour change happened before or after the onset of a brief reference (R) flash presented 4.8 deg below the moving trajectory. The size, shape, and luminance of the achromatic reference
stimulus was identical to the same parameters of the moving test. The reference was presented during one refresh cycle of the screen that lasted about 5 ms. In the other task, space judgment, the observer’s instruction was to decide whether the location of colour change was before or after the position to which the reference bar was indicating.

The judgments were made by the method of adjustment. Adjustments were done by pressing one of two predefined keys on the computer keyboard. By using these keys, the observer was able to control either the onset time \( t_R \) (time judgment) or spatial position \( s_R \) (space judgment) of the reference flash. In the time judgment series, the reference flash was initially set at 150 ms before \( (t_R - t_T = -150 \text{ ms}) \) or after \( (t_R - t_T = +150 \text{ ms}) \) the moment of colour change. After each presentation, the observer changed the onset time of the reference flash in 25 ms steps forward or backward in time until the perceived synchrony with the time of the colour change was achieved.

In the space judgment trials, the initial position of the reference stimulus was displaced up to \( s_R - s_T = \pm 144 \text{ deg} \) either in the same direction (plus) or in the opposite direction (minus) to the movement direction. After each presentation, the observer was able to change the spatial position of the reference bar by shifting it 0.16 deg to the left or to the right from the previous position until the perceived spatial alignment with the location of the colour change was achieved.

Each adjustment trial was repeated until the observer indicated by a special key press that the perceived synchrony or spatial alignment was reached. The final time position \( t_R \) or space position \( s_R \) was recorded in the time and space judgment tasks, respectively. On the basis of these judgments, the relative temporal asynchrony \( \Delta t = t_R - t_T \) and spatial offsets \( \Delta s = s_R - s_T \) were found.

Because the space coordinate of the test signal was always subtracted from the space coordinate of the reference signal, a positive spatial offset indicates that the reference bar was placed in a position that was ahead of the position where the colour actually changed. A negative spatial offset, on the contrary, shows that the probe position points to the spatial location that was already passed by the moving stimulus at the moment of the colour change. Obviously, a positive spatial offset corresponds to the typical FLE. Because a reference bar placed ahead of the position of actual colour change seems to be aligned with that position, a reference bar presented exactly at the location of the colour change should appear to lag behind the moving object.

Similarly, a positive temporal asynchrony indicates that the reference bar was presented after and a negative temporal asynchrony that it was presented before actual moment when the colour changed. Let us suppose, for instance, that a positive asynchrony, between the colour change and the onset of the reference flash, is required to perceive these two events simultaneously. What would the observer perceive if these two events—the colour change and the onset of the reference signal—would occur exactly at the same time? From the symmetry principle we should expect that the perceived sequence is: the flash comes first and after some time the moving bar changes its colour. As in the case of the positive spatial offset, the positive temporal asynchrony that is needed for the apparent simultaneity corresponds to the case where location of the flash should appear to lag behind a moving object.

In the time judgment task, the spatial position of the reference bar is irrelevant. Nevertheless, before each time adjustment trial the position of the reference flash was chosen randomly from one of the following values: \( \Delta s = -1.44 \text{ deg} \) (before), 0 deg (aligned), and +1.44 deg (after). Likewise, in the space judgment task, the onset time of the reference flash is irrelevant. In the space judgment trials, the reference bar was switched on before, after, or synchronously with the moment of colour change. There were three possible values of the temporal asynchrony, \( \Delta t = -150 \text{ ms} \) (before), 0 ms (simultaneous), and +150 ms (after), in the space judgment tasks. These relatively
small values (±150 ms) were chosen because the memory for spatial position is nearly perfect during the first 500 ms after disappearance of the object (Kinchla and Allan 1969). The observers were instructed to ignore the irrelevant dimension of the reference stimulus.

In total, there were 12 (2 velocities × 2 judgment tasks × 3 positions of reference) different experimental conditions. All subjects made 28 adjustments in each of these conditions.

2.2 Results
Figure 2 shows the mean adjusted values of time $\Delta t$ (upper panel) and space $\Delta s$ (lower panel) separately for four observers. These values are plotted against the irrelevant parameter of the reference flash, its spatial position $\Delta s$ in the time judgment task and the onset time $\Delta t$ in the space judgment task.

In spite of some individual differences, several regularities can be noticed.

First, in the time judgment task the adjustments were scattered rather unsystematically around the zero; in the space judgment task they were more stable and slightly shifted towards the positive offset values. As explained above, the positive offset between

![Figure 2](image-url)

**Figure 2.** The mean adjusted onset time $\Delta t$ (upper panel) and the mean adjusted position $\Delta s$ (lower panel) of the perceived colour change for four observers (PT, RO, KL, and KK), for two velocities, 6.4 deg s$^{-1}$ (red) or 25.6 deg s$^{-1}$ (green), and for values of the irrelevant parameter $\Delta s$ (upper panel) and $\Delta t$ (lower panel). Bars refer to ±1 SEM (standard error of the mean).
the location where colour changed and the position of the reference signal corresponds to the FLE. However, even when the irrelevant position of the reference stimulus was a neutral position (Δs = 0 deg and Δt = 0 ms), the mean adjusted time and position only slightly deviated from zero, indicating that the observers were reasonably accurate in the estimation of time and place of colour change.

Second, the velocity of the target had no systematic effect on the perceived time and location of the colour change. Even though the velocity differed by a factor of 4, the adjusted values differed only slightly. For some subjects the illusory offset was larger when the speed was higher; others adjusted the larger disparity when the test stimulus velocity was lower. The repeated-measures two-way ANOVA (with velocity and position of reference as factors) did not detect any main effect of velocity on adjustment results, neither in the temporal (F₁,₃ = 1.39, p = 0.323) nor in the spatial (F₁,₃ = 2.88, p = 0.188) adjustment task.

Third, the same analysis showed that the irrelevant dimension of the reference stimulus had a systematic influence on the adjusted values. There was a clear tendency, with only few exceptions, that with the increase of the value on the irrelevant dimension, from negative to positive, the adjusted value also increased in the same direction. This regularity is particularly obvious in the space adjustment task (figure 2, lower panel). For example, when the reference stimulus was presented after the actual colour change, Δt = +150 ms, its adjusted position was also apparently shifted in the direction of motion to a position that the moving bar had not yet reached. Similarly, when the reference flash was placed ahead of the actual location of the colour change, the adjusted time of change was also earlier. The two-way repeated-measures ANOVA confirmed that, although irrelevant for the task in hand, the spatial position of the reference flash influenced its timing (F₁,₆ = 8.22, p < 0.05) and its presentation time had an effect on the adjusted position of the flash (F₁,₆ = 31.0, p < 0.001). Although the subjects were instructed to ignore the irrelevant attribute, they were obviously unable to do so. On the level of interactions between the position of the reference and velocity, the tasks differed slightly. A negligible, but statistically significant, interaction effect was discovered for the location task (F₁,₆ = 5.45, p < 0.0448), and no effect was detected for the timing task (F₁,₆ = 0.14, p < 0.872). More specifically, the position adjustment did not differ between velocities when the reference bar was presented 150 ms before the colour change. For the other two reference presentation times, the misadjustment was the larger the higher was the velocity of the moving test bar.

Was the perceived time congruent with the perceived position of the colour change? In order to get a more comprehensive picture of the results, we averaged data of all four observers. Figure 3 shows the mean relative position of the moving target (Δs, Δt) at the moment of the colour change. Two trajectories through the space–time are corresponding to two target velocities 6.4 deg s⁻¹ (continuous line) and 25.6 deg s⁻¹ (dotted line). Filled symbols show what the moving target position was in the time judgment task and open symbols what the position was in the spatial judgment task. Labels attached to each symbol refer to the sign of the irrelevant reference stimulus dimension. This figure demonstrates that it is difficult to find any consistent rule for predicting the perceived time from the perceived location of the colour change. In the case of consistent rule, the triples of filled and open symbols on each line would have had a regular relationship. For example, there was no indicating that the perceived switch point was in an approximately constant time shift from the actual moment of the colour change. The only regular pattern was related to the values of the irrelevant dimension of the reference stimulus. The mean adjusted time and position always corresponded to the order of values on the irrelevant dimension. Irrespective of movement velocity, the order of adjusted values from left to right was −s, 0, and +s in the time judgment task, and −t, 0, and +t in the space judgment task.
Discussion

In general, the results of the first experiment agree with the results reported by Cai and Schlag (2001), who discovered that the colour change is perceived simultaneously with the flash but appears to be shifted in position. We tested directly whether it is possible to predict the apparent location where this change could have happened from the perceived time of the colour change. The answer seems to be “no”. Quite paradoxically, the perceived time of the colour change was not congruent with the perceived location of the colour change. This result may have relevant theoretical consequences, because the FLE was often operationalised in terms of the spatial offset that is required to cancel an illusory lag between the moving target and the brief flash (cf Murakami 2001). When researchers are attempting to explain the FLE in terms of temporal mechanisms, hypothetical perceptual delays are derived from the amount of illusory spatial offset based on the formula of constant velocity (eg Baldo and Klein 1995; Whitney and Murakami 1998; Whitney et al 2000). Our results, on the contrary, do not support the idea that the perceived spatial lag corresponds to the proportional amount of perceptual delay. It seems very unlikely that models of spatial extrapolation and differential neuronal delay are sufficient, in their simplest forms at least.

One possible reason for this incongruency between space and time judgments is the observer’s inability to separate spatial and temporal aspects of the stimulus clearly enough. In this study, we manipulated the irrelevant attribute of the reference stimulus. Formally, it is completely irrelevant _where_ the reference stimulus is located when the task is to synchronise two events, the onset of the reference stimulus and the time when moving stimulus instantly changes its colour. Nevertheless, the observer was not able to ignore the position of the reference stimulus and tended to switch the reference

![Figure 3](image-url)

**Figure 3.** The mean relative position of the moving target ($\Delta s, \Delta t$) in relation to the reference flash for two target velocities, 6.4 deg s$^{-1}$ (circles) and 25.6 deg s$^{-1}$ (squares) averaged over four observers. The filled symbols correspond to the time judgment task and the open symbols correspond to the space judgment task. Each symbol is labelled by the value of the irrelevant flash dimension, either $\Delta s$ (time judgment task) or $\Delta t$ (space judgment task).
stimulus earlier in time when its position was before the colour change, and delay the reference stimulus onset when the reference position was after the colour change. A very similar situation was observed in the space judgment task: although it was irrelevant when the reference stimulus was switched on, the observers were not able to ignore it when the task was to estimate the location where colour has changed. This perceived location was shifted backward or forward along the movement trajectory when the reference signal was delivered before or after, respectively, the actual moment of the colour change.

Unlike perceptual tasks in which tau and kappa effects are observed, our observers estimated momentary position and time moment, not space and time intervals. Nevertheless, we observed similar changes in the perceived time under the influence of spatial position of the reference signal and the perceived space under the influence of time when the reference signal was presented. Thus, we can conclude that the observers were not very accurate in the separation of the temporal and spatial aspects of the stimulus.

One puzzling result of this study was the indifference to the movement speed. There was no systematic effect of velocity on both types of judgment, but especially on the estimation of the perceived synchrony. It looks like the decision having been made after the visual system effectively reduced velocities to a single normalised form (cf Sekuler et al 1990; Dzhafarov et al 1993). At variance with the present finding, several previous studies have shown that the amount of the FLE, like other movement-related misperceptions, varies systematically with the movement speed (Nijhawan 1994; Kirschfeld and Kammer 1999; Krekelberg and Lappe 1999; Brenner and Smeets 2000; Whitney et al 2000; Murakami 2001). At the same time, data often show quite considerable individual variability. For example, in Nijhawan's paper (1994) the spatial misalignment did grow with the velocity but the growth pattern was quite different for the two observers whose data were represented in the graphs. It is also evident that sometimes some persons do not reveal any FLE (eg Baldo and Klein 1995; Lappe and Krekelberg 1998). However, it was also shown that the Fröhlich effect, for instance, changes into the opposite offset when the speed of the movement is slower than 20 deg s\(^{-1}\) (Müßeler and Aschersleben 1998). Also our recent study on comparison of the FLE and the Fröhlich effect demonstrated that the magnitude of the FLE did not change with velocity until the velocity rose from 16.3 deg s\(^{-1}\) to 32.7 deg s\(^{-1}\) (Kreegipuu and Allik 2003). Although the relationship between the size of the FLE and velocity is absolutely essential, their exact functional relationship still remains largely unexplored.

3 Experiment 2
3.1 Method
Participants, apparatus, and method were the same as in experiment 1. As in experiment 1, the red or green test bar moved horizontally across the screen with one of two velocities (6.4 deg s\(^{-1}\) and 25.6 deg s\(^{-1}\)) and changed its colour in the middle part of the trajectory. Again, two different tasks were used. In the first, temporal adjustment task, the reference stimulus was identical to the test bar except that it was the stationary bar that was continuously visible on the screen. The reference bar was located 4.8 deg right below the position where the moving bar changed its colour. Like the moving stimulus, the reference bar also changed its colour either from red to green or from green to red. The observer’s task was to adjust the moment of the colour change of the reference bar until it appeared simultaneous with the colour change of the moving target. Before each trial, a random asynchrony between the test and reference signals was established within a window of \(\Delta t = \pm 150\) ms, and the observer changed the asynchrony after each presentation until two colour changes appeared simultaneous.
In the spatial adjustment task, an achromatic reference bar was constantly present on the screen and did not change its luminance. Before each trial, its initial position was randomly chosen in the interval $\Delta s = \pm 1.44$ deg symmetrically around the spatial position where the moving bar changed its colour. After each presentation the observer changed the horizontal position of the reference to the left or to the right in small steps. The observer’s task was to adjust the position of the reference until it appeared to be aligned with the position of the colour change.

In order to estimate the precision of adjustment, two additional control series with the stationary test bar that changed its colour were performed. In the first, the observer adjusted the horizontal position of the 5 ms reference flash until it appeared to be aligned with the position of the stationary test stimulus which appeared 4.8 deg above the reference. In the second task, the colour change of the stationary test bar was compared to the presentation moment of the 5 ms flash. The observer’s task was to adjust the appearance of the flash so that it was simultaneous with the colour change.

Repeated adjustments in each experimental condition were approximated by a Gaussian function. The precision of adjustment, corresponding to the classical concept of the just noticeable difference, was measured as the distance or the time interval between 25% and 75% points. All four subjects made 21 adjustments in each experimental condition.

3.2 Results

The results of four observers in two adjustment tasks are combined in figure 4. Filled circles and the right scales of each panel correspond to the time judgment task. Empty squares and the left scales correspond to the spatial judgment task. The general pattern of the results is very similar to that in the first experiment. All four observers were

![Figure 4](image-url)

**Figure 4.** The mean adjusted onset time $\Delta t$ (filled circles and the right scale) and the mean adjusted position $\Delta s$ (empty squares and the left scale) of the perceived colour change in relation to a stationary reference as a function of velocity, 6.4 deg $s^{-1}$, or 25.6 deg $s^{-1}$, for four observers (PT, RO, KL, and KK). Boxes represent $\pm 1$ SEM (standard error of the mean), and whiskers are 95% confidence interval.
Relatively close to the zero line in the time judgment task. Thus, the moving stimulus appears to change its colour approximately simultaneously with the similar change of colour of the stationary reference stimulus. In the space judgment task, however, observers tended to put the reference in a location that was ahead of the place where the moving stimulus changed its colour (see figure 4). The positive adjustment error, as we explained above, designates conditions that are typical of the FLE. In this case, however, the reference stimulus was not a short flash. It was constantly visible throughout the whole test trial. Consequently, it is not necessarily the flash as such that is processed differently from moving objects.

As in the first experiment, velocity played no significant role in both time and space judgment tasks. The apparent location of colour change did not change much when the velocity of the test stimulus increased from 6.4 deg s\(^{-1}\) to 25.6 deg s\(^{-1}\).

As expected, the observers were accurate in alignment of two stationary flashes and they did it with a sufficient consistency. The mean precision of adjustments, measured as the just noticeable difference, across all four observers was 8.9 min of arc. For comparison, the estimated location of the colour change of the moving target was significantly more unreliable. The mean adjustment precision was 44.1 and 49.1 min of arc respectively in the first and the second (present) experiment. There was not such a sharp contrast between stationary and moving stimuli in the time judgment tasks. The mean precision with which the simultaneity of the colour change of the stationary bar and the flash was judged equalled 59.6 ms, which is typical of the discrimination of temporal order of two perceptual events (e.g. Hirsch and Sherrick 1961; Allik and Kreegipuu 1998). When the colour-changing stimulus was moving, the precision with which the perceived moment of transition was reproduced deteriorated slightly: to 78.3 and 77.1 ms, respectively, in experiments 1 and 2.

4 General discussion
Because the results of the first and the second experiment were in an agreement, we can conclude that the reference flash is not critical for the occurrence of the FLE. The perceived spatial lag can be also observed when the reference signal is constantly visible and its location is adjusted with the perceived location of the colour change. It has been common to explain the illusion by differential perceptual latencies: it takes longer time to perceive a brief flash than a constantly visible moving stimulus and for that reason the moving object appears as if it was ahead of the flash. Besides pure processing time (Whitney and Murakami 1998), the temporal differences can be also due to attention: the attended stimulus, this time the moving one, enters consciousness earlier than an unattended and unexpected flash (Baldo and Klein 1995). However, explanations in terms of latency differences are untenable because we observed an apparent lag without a flashing reference stimulus.

Besides temporal explanations, some spatial mechanisms, either in the form of extrapolation (Nijhawan 1994) or distant-movement-dependent positional shift of the stationary object (Whitney and Cavanagh 2000) are provided for the FLE. Although the pure extrapolation has been repeatedly refuted (e.g. Whitney and Murakami 1998; Brenner and Smeets 2000; Eagleman and Sejnowski 2000a), some combination of spatial and temporal mechanisms is very likely in assigning the position to a moving object (Whitney 2002). Thus, in the adjusted position of the flash, the attention, different latencies, and distant motion (and some other mechanisms) together may have been contributing. At least some of these mechanisms (e.g. distant motion) most probably do not work in the timing system—the aspect that may be responsible for the differences between our spatial and temporal conditions. If this were true, the 'extra' mechanism that contributes only to the spatial lag has to have considerable temporal sensitivity.
This reasoning agrees with Eagleman and Sejnowski's (2000a) view of position assignment as a quite complicated process in the human perceptual system.

As we mentioned in the introduction, our colour-changing stimulus was inspired by a paradigm introduced by Moutoussis and Zeki (1997). They presented a pattern periodically moving up and down. When a green pattern moving upward and a red pattern moving downward were alternated every 250 ms, most observers had difficulties with saying which direction and colour were shown together. However, when the direction change occurred about 100 ms earlier than the colour change, the observers reported that both changes occurred simultaneously. This subjective delay of motion change was interpreted as indication that the conscious perception of motion requires more time than that of colour. If indeed the perception of colour is faster than that of motion, we could expect that in our experiment the observer would indicate the locations that are before the actual colour change. In fact, as the results demonstrate, the observers pointed to the locations that were ahead of the position where the moving target changed its colour. In terms of the processing time, this means that the perception of colour requires more time than that of motion. However, the interpretation of these subjective delays directly in terms of processing time is doubtful.

Nishida and Johnston (2002) demonstrated recently that the observer can make decisions about the synchrony of colour and movement changes accurately in one stimulus condition but fail in another. For example, temporal relationships can be veridically judged at low movement and direction alteration rates, although for rapid direction changes an illusory delay is introduced. A slight change in the task may give completely different results. For instance, the observer could accurately synchronise the unseen movement of a computer mouse with the movement seen on the screen of the computer. But they reported an approximately 100 ms delay when the observers had to indicate movement-direction changes in a button-press experiment (Nishida and Johnston 2002). Similarly, Brenner and Smeets (2000) found that the perceived spatial lag in the FLE is substantially decreased or abolished when the observer has a possibility to rely on additional temporal cues. These results indicate that there are different accesses to internal neural representation and different information can be extracted under these slightly varying instructions.

The individual variability observed in the time and space judgment tasks indicates a flaw in the assumption that the adjusted asynchrony, $\Delta t$, and spatial lag, $\Delta s$, automatically correspond to the perceptual ‘time’ and ‘space’. It is more than just plausible that some internally established criteria, strategies, and higher-level cognitive factors are involved in the judgment of the simultaneity and spatial alignment of two visual events, one of which is a moving object. There is an accumulating amount of evidence that attention (eg Baldo et al 2002) and more ‘cognitive’ variables (eg Bachmann and Pöder 2001; Watanabe et al 2001) are also involved in the FLE. The relatively large individual variability and unresponsiveness to velocity that was observed in this study seem to suggest that the ‘momentary position’ of the moving object is a poorly defined concept (see also Eagleman and Sejnowski 2000a), probably due to nonuniformity of brightness along the moving shape. The reduction of the judgment precision strongly supports this conclusion. It is well known that the moving object appears to be distorted. For example, the leading edge of a moving bar appears to be smeared and it leaves behind a decaying ‘comet tail’. The observer can identify different parts of this moving luminous body and, as our results seem to suggest, uses different criterion positions for different velocities (cf Dzhafarov 1992c).

Morgan and his colleagues (Morgan et al 1990) have argued that visual illusions may arise when observers are instructed to carry out a task to which the visual system is not adapted. The number of visual tasks that visual system is able to solve is fundamentally limited. When facing a task for which the visual system is not adapted,
it often happens that another task is solved and the solution is provided as an answer to the original question. This is what seemed to happen in the present experimental situation.

5 Conclusions
This study provided answers to three posed questions.

First, by using the colour-change method we were able to separate the perceived time of some visual event from the perceived location of the same event. Somewhat surprisingly, we did not find that these two percepts are congruent with each other. Like Cai and Schlag (2001), we found that the colour change is perceived simultaneously with the reference flash but shifted in position.

Second, we discovered a strong influence of the irrelevant stimulus dimension on the judgment of space and time. This influence indicates that the observer is not able to separate spatial and temporal aspects of the stimulus.

Finally, we found that the apparent spatial misperception can be obtained even without using a flash as a reference stimulus.

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