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Perceived onset time and position of a moving stimulus

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Abstract

During the few past years, there has been a growing interest in the timing and locating of moving stimuli. The most popular spatio-temporal phenomena that have been studied are the flash-lag effect (FLE) [Nature 370 (1994) 256] and the Fröhlich effect (FE) [Z. Sinnesphysiol. 54 (1923) 58]. Most often these phenomena are examined by some spatial task (e.g., judging whether moving and flashed stimuli are spatially aligned or not; explicitly pointing or adjusting the moving stimulus position). Usually, from the measured spatial offset temporal differences in processing of moving and stationary stimuli are inferred. Our experiments show that this practice may not be justified because the spatial and temporal properties were clearly disassociated for the movement onset perception. The disassociation demonstrates that the FLE and FE are most probably based on different internal representations.

Keywords: Movement onset; Velocity; Spatio-temporal sensitivity

1. Introduction

Psychophysicists have been mainly interested in the observer's ability to judge the principal properties of a moving stimulus: the presence or absence of motion, its perceived direction and velocity. But aside from deciding whether something is moving, in which direction or with what speed, it is also relevant, at least in some cases, to know where exactly the moving object was at a given moment in time. Many tasks, like catching, hitting or avoiding a fast-moving object, require an extraordinary high precision in the specification of the moving object's spatial and temporal coordinates. The ability is amazing because it is known that excitation of visual receptors and transmission of the visual information from retina to the higher brain areas or consciousness inevitably takes at least 40–60 ms. Thus, the information about a fast-moving object reaches the brain when its current location has already changed considerably.

2. Two spatio-temporal phenomena: the flash-lag effect and Fröhlich effect

During the past few years, however, interest in the ability to estimate the timing and location of a moving object has increased particularly due to the rediscovery of the *flash-lag effect* (FLE, Nijhawan, 1994, 1997, the phenomenon that has been repeatedly described earlier by many researchers, including MacKay, 1958). A typical task is to judge whether a moving and a flashed stationary stimulus are spatially aligned (e.g., Baldo & Klein, 1995; Brenner & Smeets, 2000; Eagleman & Sejnowski, 2000a; Kirschfeld & Kammer, 1999; Müsseler, Stork, & Kerzel, 2002; Nijhawan, 1994, 2001; Purushothaman, Patel, Bedell, & Ogmen, 1998; Whitney, Cavanagh, & Murakami, 2000). What was often discovered is that, for the perceived alignment of these two stimuli, the flash should be delivered earlier in time, at the moment when the moving stimulus has not yet reached the flash's position. The reported phenomenon seems to be quite robust because it was obtained in various experimental settings that included different eccentricities, a wide range of velocities and different trajectories of movement. The magnitude of the mislocation can also reach a considerable magnitude, in many cases about 1°–2°.

Another well-known phenomenon of apparent mislocation of a moving object was discovered by Fröhlich who observed that a rapidly moving object coming out from an occluding edge was seen to appear not at the edge, but only at some distance from the edge in the direction of motion (the *Fröhlich effect* or FE; Fröhlich, 1923, 1929). Similar mislocalization occurs not only in

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the case of the appearance of a moving object but also in the case of its disappearance: the final perceived location appears to be displaced from the actual disappearance position in the direction of movement (the phenomenon called *representational momentum*, see e.g., Freyd & Finke, 1984; Hubbard & Motes, 2002; Kerzel, 2002). In a typical FE experiment the observer is asked to indicate the location in which she or he first saw the appearance of the moving object.

2.1. One or two different mechanisms for the FLE and FE?

There is no generally accepted explanation of the FLE or FE, perhaps two most intensively studied mistiming and/or mislocalization phenomena. It is also unclear whether the FLE and FE can be explained by the same perceptual mechanisms or whether it will be necessary to invoke two different mechanisms. Some explanations of the FLE, for instance, seem to be applicable for the FE as well. For example, the differential perceptual latency model (Baldo & Klein, 1995; Mateeff, Bohdanecky, Hohnsbein, Ehrenstein, & Yakimoff, 1991; Mateeff, Yakimoff, et al., 1991; Patel, Ogmen, Bedell, & Sampath, 2000; Purushothaman et al., 1998; Schlag & Schlag-Rey, 2002; Whitney & Murakami, 1998; Whitney, Murakami, & Cavanagh, 2000) explains the FLE with the time difference between processing the moving and suddenly appearing stimuli. Parallel attempts have been made to explain the FE in terms of perceptual delay (Aschersleben & Müsseler, 1999; Kirschfeld & Kammer, 1999; Müsseler & Aschersleben, 1998). However, it is important to notice that Fröhlich's (1923, 1929) original "sensation time" explanation is not a differential time explanation. Fröhlich proposed that the perception of the initial part of a moving stimulus is not delayed but simply absent from the conscious representation.

Besides the Kirschfeld and Kammer's (1999) study, Eagleman and Sejnowski have proposed a mechanism that could potentially explain both mislocalization phenomena (Eagleman, 2001; Eagleman & Sejnowski, 2000a, 2000b, 2000c, 2002). The main tenet of their explanation is that the position of the moving object is not an elementary sensation but a result of a complicated reconstruction. The process of assignment of perceived locations is postdictive in its character and depends on events happening after the critical moment; it also needs to be specially initiated, and at the same time, to be based on quite precise temporal sense. The corresponding instant position attributed to the moving item is the result of the interpolation of moving object's recent positions and therefore can deviate from the actual position as it is the case with the FE and FLE. In principle, the FLE and FE can be explained by the same interpolation mechanism.

The first step towards a unified explanation is congruence between different measures of the FLE and FE. For instance, Aschersleben and Müsseler (1999) compared different tasks (localization, several reaction time (RT), temporal order judgment (TOJ) and synchronization experiments) and found substantial dissociation between these tasks. They concluded, we believe rightly, that measures of the FE do not reflect directly sensory representation but are based on later interpretative processes. As synchronization and choice RT task on structural features showed delayed processing of the moving stimulus as compared to a stationary one, they also conclude that the FE is not a pure localization effect but refers to the temporally delayed timing of the moving object (Aschersleben & Müsseler, 1999, p. 9).

Recently, Whitney and Cavanagh (2000) observed that a valid stationary cue abolished the FE but did not affect the FLE. From this dissociation they concluded that these two effects cannot be explained in the same way. Although Eagleman and Sejnowski (2000c) pointed to some weaknesses in Whitney and Cavanagh's (2000) design, their data show at least some dissociation between the FLE and FE. One possible reason for this dissociation is that the beginning, middle-phase and the stopping movement may be processed differently. Indeed, the FE is a phenomenon associated with the movement initiation and the FLE with the middle-phase. Müsseler et al. (2002) measured mislocalization of the moving object in different movement phases and found that both localization and phenomenology varied with the phase. Nevertheless, Müsseler and his colleagues supposed from the parsimony principle that only one mechanism could be behind these effects. It is not very difficult to suggest a localization mechanism the result of which depends on the movement history that generates different results for the beginning, middle, and the end phase of movement.

2.1.1. Attention

The "sensation time" idea, originally proposed by Fröhlich, is similar to more recent explanations formulated in terms of attention. It is well known that when attention is allocated to the to-be-perceived object (either moving or not), the perception time is shorter than for the unattended item (Posner, 1995; for experimental data on the FLE and FE see Kirschfeld & Kammer, 1999; Khurana, Watanabe, & Nijhawan, 2000, the reaction time condition). This is also known as a concept of prior entry (e.g., Shore, Spence, & Klein, 2001; Titchener, 1908). One possible explanation of the speed-up of the attended stimulus is that attended and non-attended stimuli are channeled through different neural pathways with different transmission speed (Bachmann, 1999, 2000). Thus, if attention was a factor in these spatio-temporal phenomena, the flash should lag the moving object because the flash serves as a marker that indicates the need to attend (the position of) the moving object. No information is available during the "jump" towards the moving object or the pure signal transmission time from the retinal periphery. When finally the moving item has been attentionally captured, it has moved to a later position in its trajectory that naturally produces the misalignment. The same logic is valid for the FE as well: suddenly appearing object in the visual field catches attention, and while the attention is allocated to the object, its position has already changed. If this were true, the amount of misperception in both effects should depend positively on the sensory factors such as range of velocities, eccentricities or luminance and on the duration of the "process of attentional capture" that could be manipulated by varying the task instruction and stimulus salience. The attention shift position is held by several researchers (e.g., Aschersleben & Müsseler, 1999; Baldo, Kihara, Namba, & Klein, 2002; Baldo & Klein, 1995; Müsseler & Aschersleben, 1998; in the form of "*predictability* of continuous rotating segment and *unpredictability* of the strobed segments" also by Nijhawan, 1994, italics added).

One of the easiest ways to manipulate attention is to change instructions or present valid cues in the FLE and FE experiments (e.g., Kirschfeld & Kammer, 2000). Baldo with colleagues (Baldo & Namba, 2002; Baldo et al., 2002, Haddad, Carreiro, & Baldo, 2002) has explicitly tested the role of attention in the FLE and showed that the result depends very much on the task. The magnitude of the FLE increased with the decreased predictability of the flashes' eccentricity or position. A similar effect of valid cue was observed also for the FE by Müsseler and Aschersleben (1998) and Kerzel and Müsseler (2002). At the same time, in Khurana et al. (2000) study, the FLE did not change qualitatively when prior knowledge about the location of the flash or particular moving object the position of which had to be compared to the flash, was given or not. On the basis of experiment 3 they concluded that attention can indeed speed up processes and modify delays (when measured by RT) but does not change the phenomenological perception itself.

Although the way how attention is allocated is important, it may be insufficient to overcome illusions. For example, Khurana and Nijhawan (1995) tested endurance of the FLE by using two spatially overlapping simultaneously presented stimulus configurations (later also used by Eagleman & Sejnowski, 2000a) and in spite of the two competing perceptions flashes still lagged behind the moving objects as much as in isolation. The phenomenal equality of the flash-initiated cycle (FIC) and the complete cycle (CC) design (Khurana & Nijhawan, 1995) seems to be a very strong argument against attention related sensory explanations of the FLE. However, this is not the whole story. Differential processing of the sensory information depending on its position in stimulus array has been demonstrated for the FLE and FE (see Bachmann & Põder, 2001, Fig. 2; Krekelberg & Lappe, 1999, Fig. 5; or Müsseler & Aschersleben, 1998, Fig. 6, respectively). The FLE has been also demonstrated to depend on the flash's position relative to movement trajectory: the effect was considerable at the movement onset, reduced around the trajectory's mid-point and reversed for the offset (Müsseler et al., 2002). An additional reason for considering attentional or other interpretative mechanisms is derived from experimental demonstrations that FLE-like phenomena can be elicited with a non-moving stimulus (Bachmann & Põder, 2001; Sheth, Nijhawan, & Shimojo, 2000).

Either in conjunction with attention or independently, several stimulus parameters like velocity, eccentricity or luminosity have been demonstrated to influence the magnitude of both effects. If the patterns of dependencies were similar across the effects, it would possibly serve as an additional evidence of the same underlying mechanism and vice versa. Next we introduce some relevant findings and demonstrate that as much as we were able to uncover from the literature, at least the FLE shows also remarkable individual variability.

2.1.2. Velocity

A typical finding is that the spatial lag in the FLE or FE experiments increases with the increase in movement velocity. In previous studies, several tangential velocities of visual angle per seconds have been employed, for example 1.02–3.06°/s (Nijhawan, 1994), up to 90°/s (Kirschfeld & Kammer, 1999), 1–7°/s (Krekelberg & Lappe, 1999), approximately 11–28°/s (Lappe & Krekelberg, 1998), 6–14.5°/s (Mateeff, Bohdanecky, et al., 1991, spatial misalignment task). Data from Mateeff, Bohdanecky, et al. (1991) are particularly interesting because their experiment on temporal localization of the moving object relative to a reference at the time of a click showed no effect of stimulus velocity on the empirical perceived moment of perceptual simultaneity. At the same time the data revealed a strong effect of velocity on the calculated point of subjective misalignment. For the FE, the regularity can be extrapolated (see Müsseler & Aschersleben, 1998, who used stimuli moving at 14.3 and 40°/s), until somewhere below the speed of 20°/s, the effect disappears (Kerzel, 2002; Kerzel & Müsseler, 2002) or the opposite shift of the first perceivable position of the moving object—the *onset repulsion effect* (ORE, Hubbard & Motes, 2002; Kerzel, 2002; Thornton, 2002) occurs. Kerzel (2002) has demonstrated that the effect of velocity on the FE depends on the task: the regularity is valid for relative judgments but no FE was obtained at any velocity when the pointing task was used. Thus, the effect should be perceptual, nor motor or relying on the content of the short-term memory. No similar velocity dependent reversion for the FLE is known.

2.1.3. Eccentricity

The eccentricity of flashing dots was a factor in Baldo and Klein's (1995) experiment: when the distance between moving and flashing dots increased more than three times (1.45° and 4.74°), the relative misalignment increased by the factor of 2.5. Also in the reversed version of the experiment (i.e., having flashes in the center and moving dots at outer positions), the FLE was smaller which fits to the eccentricity and attention account. Comparable results come also from Baldo et al. (2002). In another study from Baldo and his colleagues (Haddad et al., 2002), the effect of attention was separated from the effect of the eccentricity of the peripheral flash. Presenting the flashes at different eccentricity in separate blocks (4.8° and 9.6° or 2.5°, 7.3° and 12.1°) abolished the effect of the eccentricity that was revealed in conditions where the flash's distance from the central dot varied randomly from trial-to-trial. Müsseler and Aschersleben (1998) found the same for the FE: completely randomized sequence of eccentricities between 1° and 9.5° did not reveal any difference in the mislocalization of the first position of a moving bar. Thus, not the flash's eccentricity alone but also its predictability modulates the perception of the presentation time. Eccentricity did not affect the results in the mislocation in the Lappe and Krekelberg's (1998) experiment on comparing the position of continuously moving dots.

2.1.4. Luminocity

Dependence of the FE on stimulus intensity is as old as the effect itself (Fröhlich, 1923). It is also known for more than a hundred years already that visual latency decreases when stimulus luminance increases (e.g., Exner, 1868; Hess, 1904). If the FLE was a result of differential latencies between the moving and flashed stimuli, it would be possible to modify the effect by varying either object's intensity. This is exactly what takes place (Lappe & Krekelberg, 1998; Purushothaman et al., 1998). Purushothaman et al. (1998) even got the "flash-lead effect" when the detectability of the flashes was increased.

2.1.5. Individual variability

One important aspect in the published FLE and FE data is the individual variability that is usually ignored and not reported. In one of the few studies where data are available, Baldo and Klein's (1995) one observer out of five did not express any FLE neither for the closer nor the more distant flashes. The flash-lead effect due to low-luminance moving line and high-luminance flash was observed in three out of four observers in Patel et al. (2000). In Khurana et al. (2000) a variability of responses was considerably smaller for an author of the experiment than for the other, a naive observer. In Lappe and Krekelberg (1998, Figs. 3 & 4) the flash-duration or flash-frequency dependent FLE varied by the factor of 2 or 3 between participants. Similar variability is present in Krekelberg and Lappe (1999, see Fig. 4). In the high-frequency limit condition where the position of rotating outer and inner dots was compared, one observer even showed the opposite lag (Lappe & Krekelberg, 1998, Fig. 6).

2.2. Temporal vs spatial processing

With the few exceptions, the FLE and FE are usually measured in terms of spatial misalignment. It is tacitly assumed that the perceived location corresponds to the perceived timing of the same event. Only few researches have proposed an asymmetry between space and time. For instance, the explanation proposed by Eagleman and Sejnowski (2000b) assumes a higher precision for the comparisons in the temporal than in the spatial domain. The latter was shown also by Brenner and Smeets (2000) who modified the FLE very easily by only slightly changing the stimulus configuration. They used a localization task (i.e., to indicate whether two outer circulating dots are aligned with a central flashed bar or not) but in one condition the position where the flash could appear was always visible. The modification made the original localization task solvable also in time domain (i.e., estimating when the dots pass the line, before or after the flash). This small change was enough to reduce the FLE substantially or even completely abolish it. The position also fits with Mateeff, Bohdanecky, et al. (1991) data that showed constant and velocity independent latency difference in timing of the stationary and moving stimulus that correspondingly means increasing localization errors with increase in velocity. An opposite position is held by Nishida and Johnston (2002) who proposed that the visual system is relatively imprecise in the assessment of the temporal order of visual events using a simplified strategy for it. These authors provided compelling evidence that the visual system is not able to monitor all visual events but is assigning temporal markers only to the few salient changes. The temporal markers are not identical to the events or their content, but are somehow bound to the event. Because the observer's judgments are based on the markers, not the events themselves, mistiming and mislocalization are likely to occur. Thus, although the general practice in the FLE and FE research is to measure space and make inferences about the processing times, not all approaches to the FLE or FE necessarily state the equality of the temporal and spatial processing.

2.3. Goal of this study

The main goal of our study was to compare the FE and FLE to find out whether these two effects are based on the same internal representation. Our strategy was to measure both perceived spatial position and time of the movement onset. Provided that the perceived space and position are congruent, it would be logical to expect that from the perceived spatial position it is possible to predict the perceived onset time of the same visual event and vice versa. Surprisingly, our data clearly indicate a dissociation between these two measures.

3. Method

3.1. Observers

Four observers, all females, with normal or corrected-to-normal vision participated in the experiments. Two participants were experienced in psychophysical experiments, the two others were not. Their mean age was 23.8 years (SD = 2.1 years, age ranged from 22 to 26).

3.2. Apparatus and stimuli

Stimuli were generated using Cambridge Research Systems VSG 2/3 and presented on an HP 19 in. monitor. The refresh rate of the screen was 200 Hz. From the 1.4 m viewing distance the screen size was 14.9° horizontally and 9.6° vertically. The whole screen served as a background with an intensity of 1.3 cd/m^2. A white 0.16° by 1.23° vertical bar with the luminance of 19.4 cd/m^2 served as a test stimulus (T). In all conditions the test stimulus T started to move from the center of the screen either to the left or right with the constant speed 4.2, 8.2, 16.3, or 32.7 °/s. The direction of the movement, to the right or left, was randomly chosen before each trial. The target's position was updated after each 5 ms and the velocity depended on the step size in pixels. For all velocities, the impression of the motion was rather smooth. A control series with a stationary T were also performed ($v = 0$°/s).

The method of constant stimuli was used to estimate the perceived position and time of onset of the moving stimulus. For that the onset of movement was compared with a reference stimulus. Both timing and location judgments were made with the reference of a stationary probe bar (P) the width, length and luminosity of which were identical to those of the moving test stimulus. In the center of the screen there was a small fixation cross. The test and probe stimulus were vertically separated by the 0.23° and appeared symmetrically on and below the fixation cross (see Fig. 1). Stimulus onset asynchronies (SOAs) or relative position (ΔX) between the moving test bar and the centrally located stationary probe ranged with 6 equal steps from −150 to +150 ms, or $-11.1'$ to $+11.1'$ (plus corresponds to the temporal order "probe-before-test" and the movement direction throughout the study). The fastest moving stimulus (32.7°/s) reached the edge of the screen 228 ms after the beginning of the movement and for the slowest stimulus (4.2°/s) it took 1774 ms to cover the same distance. The presentation time of the probe depended on the movement speed and the observer's behavior. Usually the probe stayed on the screen until the response came or until the test bar disappeared behind the edge of the screen (all velocities except the fastest when an extra 800 ms was added to the probe visibility after the disappearance of the test bar). The last modification was introduced in order to equalize probe visibility time for different velocities.

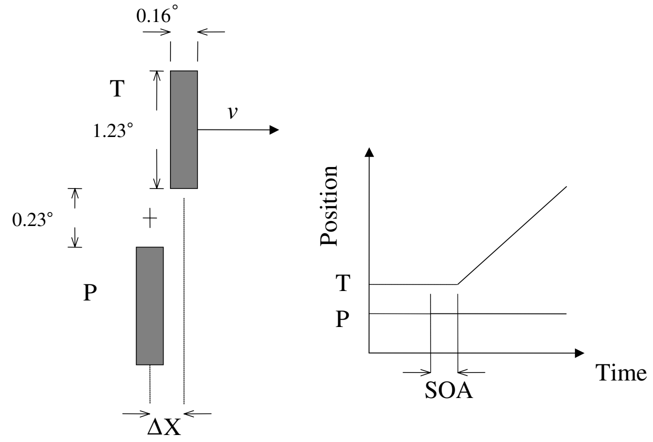

Fig. 1. Experimental display and presentation of stimuli. Different tasks—estimation of the relative onset time (SOA) or position (ΔX) of the moving test-bar (T)—and velocities (0, 4.2, 8.2, 16.3, 32.7°/s) were presented in separate blocks in pseudo-randomized order. When the onset moment or position of the moving item was estimated, the other parameter was zero. In the temporal order task the SOA was −150, −100, −50, 0, 50, 100, 150 ms. In the position task, the ΔX was $-11.1'$, $-7.4'$, $-3.7'$, $0'$, $3.7'$, $7.4'$, $11.1'$. T's and probe's (P) intensities were equal (19.4 cd/m^2), and they were presented on a dark background (1.3 cd/m^2). The viewing distance was 1.4 m.

The number of repetitions per data point per observer was 60 per each condition. Observations took place in a dimly lit room.

3.3. Procedure

Observers were instructed to keep their eyes on the fixation point and solve one of two tasks: (1) to decide whether the probe bar appeared before or after the start of movement and (2) to judge if the starting position of movement was to the left or right from the position indicated by the probe. Every trial started 700 ms after the answer of the previous trial was given. If the response was not given within 5 s, it was considered timed out and the next trial was initiated after a short sound signal and 800 ms delay. The timed-out trials were later randomly re-presented. The set-up allowed observers to take a break if they needed it. All responses were given on the computer keyboard. No feedback was provided. The sequence of the conditions (either tasks or velocities) was block-wise pseudo-random.

The distribution of timing and spatial position judgments were approximated by the cumulative normal distribution (Quasi–Newton method of approximation with least square errors). The mean of the distribution represents *the point of subjective equality* (PSE) and the variance indicates the discriminative ability. At the PSE value of 0.5 the moving test bar seemed to be simultaneous or spatially aligned with the stationary probe. Corresponding values on the abscissa refer to the physical presentation of stimuli in the test. In the time domain, the positive value of the PSE means that the moving stimulus was actually presented later than the probe. Correspondingly, the negative PSE means that the moving stimulus was presented earlier than the stationary stimulus. In the localization task, the left–right positions were changed into relative positions in terms of direction of the movement, and the PSEs were calculated again. The positive PSE indicates that the moving bar was presented in a position that was shifted into the direction of the movement. The negative value of the PSE refers to a situation where the moving stimulus was first presented in a position opposite to the movement direction. Thus, the positive PSEs refer to the FLE or FE.

In order to estimate the discrimination ability, the *just noticeable difference* (JND) was found from the slope of the psychometric function. Computationally, JND was defined as a stimulus interval between the 0.5 and 0.75 points of the psychometric curve. PSE and JND values were found for all 50 experimental conditions: 2 tasks (localization and timing) × 5 observers (4 participants and their average) × 5 velocities. The goodness of fit was estimated by the squared correlation between empirical data points and their predicted values, r^2, which was in 90% of cases larger than 95%. The only fit below 90% ($r^2 = 84.2\%$) emerged in timing task with the 16.3°/s (observer TK). The other fits below 95% were distributed randomly across velocities. As expected, the average data from all four observers and the stationary test conditions showed almost perfect fit.

4. Results and discussion

The estimated PSE and JND values for both timing and locating tasks are shown in Fig. 2. The two upper panels (A and B) correspond to the onset time judgment and the two lower panels (C and D) correspond to the localization judgments. Left panels (A and C) show the absolute error or PSE of judgments with standard errors for the averaged data points and the right panels (B and D) show the precision of judgments in terms of the JND. As expected, for a stationary test stimulus (zero velocity) both the perceived onset time and the perceived position were very close to the actual time and location of the test stimulus. For a moving stimulus, however, some shifts in the perceived onset time and location occurred. Despite individual variability, there was a general trend to anticipate the probe in order to perceive it in synchrony with the beginning of the movement (Fig. 2A) that generally refers to the FLE. Particularly at the highest velocity (32.7°/s) we can see that all observers agreed that in order to achieve the apparent simultaneity, the stationary probe should have occurred about 40 ms before the moving bar. However, the precision of temporal discrimination was relatively poor (Fig. 2B): around 30 ms when onsets of the two stationary bars were compared and rising to 60–70 ms when the onset time of movement was judged.

In contrast to the timing, the estimation of the location was nearly perfect (Fig. 2C): the constant error did not depend on velocity ($F_{4,12} = 1.22$; $p < 0.353$, *repeated measures ANOVA*). If there was any tendency at all to mislocalize the movement onset, it was only slightly biased to the movement direction. Thus, no reliable FE was observed in this particular judgment instruction and under those experimental conditions. The precision of spatial discrimination was an increasing function of velocity (Fig. 2D): on average, the imprecision of discrimination increased from about 1 min at zero velocity to about 6′ at the highest 32.7°/s velocity.

The results of these two tasks, timing and localization are strikingly different: the movement localization task was much more accurate than the timing task. The difference between these two tasks becomes particularly obvious when we transformed the observed time error into corresponding spatial error and vice versa, the observed spatial displacement into a corresponding temporal delay. This was done in Fig. 3 for both types of judgment, timing and localization. Fig. 3 is a replica of Fig. 2 except that instead of the observed values the hypothetical predicted values are displayed. Averaged experimental data from Fig. 2 are re-plotted as a dotted line. The perceived onset time predicted from the results of the spatial judgment (Fig. 3A) should be almost errorless, clearly different from the actually estimated onset time (dotted line). Also the precision of temporal discrimination (Fig. 3B), predicted from the result of position judgments is many times more accurate than in reality. In contrast, the position errors computed from the respective temporal onset judgment errors are huge compared with the actual precision of spatial discrimination. Both, PSEs (Fig. 3C) and JNDs (Fig. 3D) are much smaller than would be predicted from data of temporal discrimination.

4.1. Control conditions

One reviewer pointed out an alternative possibility, that the moving bar could "fluctuate" (Patel et al., 2000), that is the moving bar could seem to be stationary for a while, and then start to move. One obvious reason

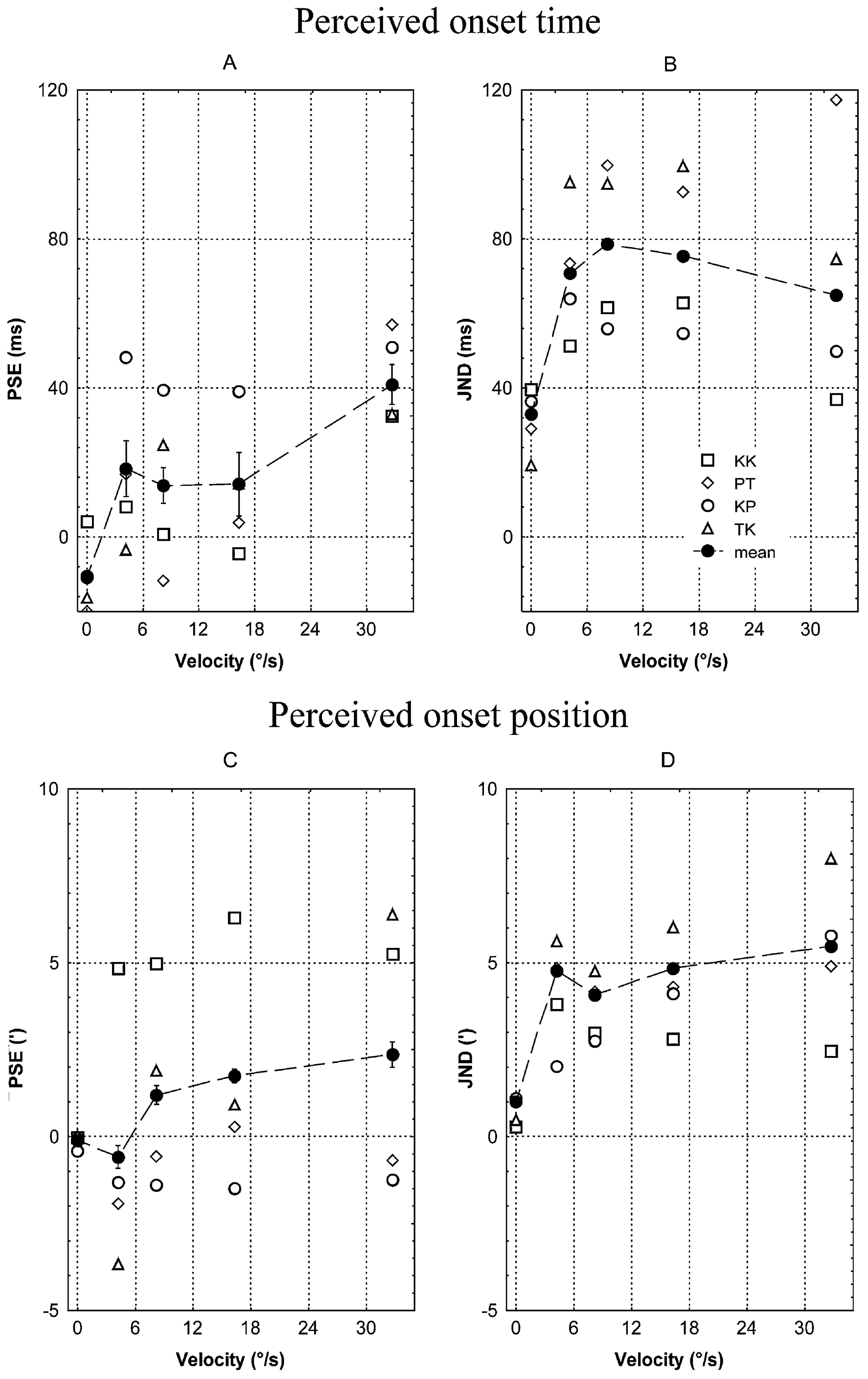

Fig. 2. Constant errors (PSE) and discrimination ability (JND) for timing or locating of the moving bar. Part A shows *when*, and part C shows *where* the moving bar was first perceived. Error bars in A and C represent ± standard errors. Part B and D represent discrimination ability for timing and localization tasks respectively. Line graphs represent averaged data for four observers together. Scatter-plots refer to individual data ($n = 60$). Positive PSE in graph A and C may be interpreted as the indicators of the shorter processing time of the moving stimulus.

for this kind of fluctuation is the conjunction of two visual events—the appearance of the stimulus and the beginning of motion. In order to separate the motion onset from the stimulus appearance, we repeated the timing experiment with "stop-go" motion. First a stationary bar appeared and stayed in the same position for a random foreperiod of 600–2400 ms which it started to move with a constant velocity 4.2, 8.2, 16.3, or 32.7°/s. All other conditions were identical to the original timing task. As in the original experiment, the probe was presented up to ±150 ms around the motion onset.

We compared the averaged PSEs obtained from the timing tasks with two kinds of movement (either the original task's "go"-type of movement or the control

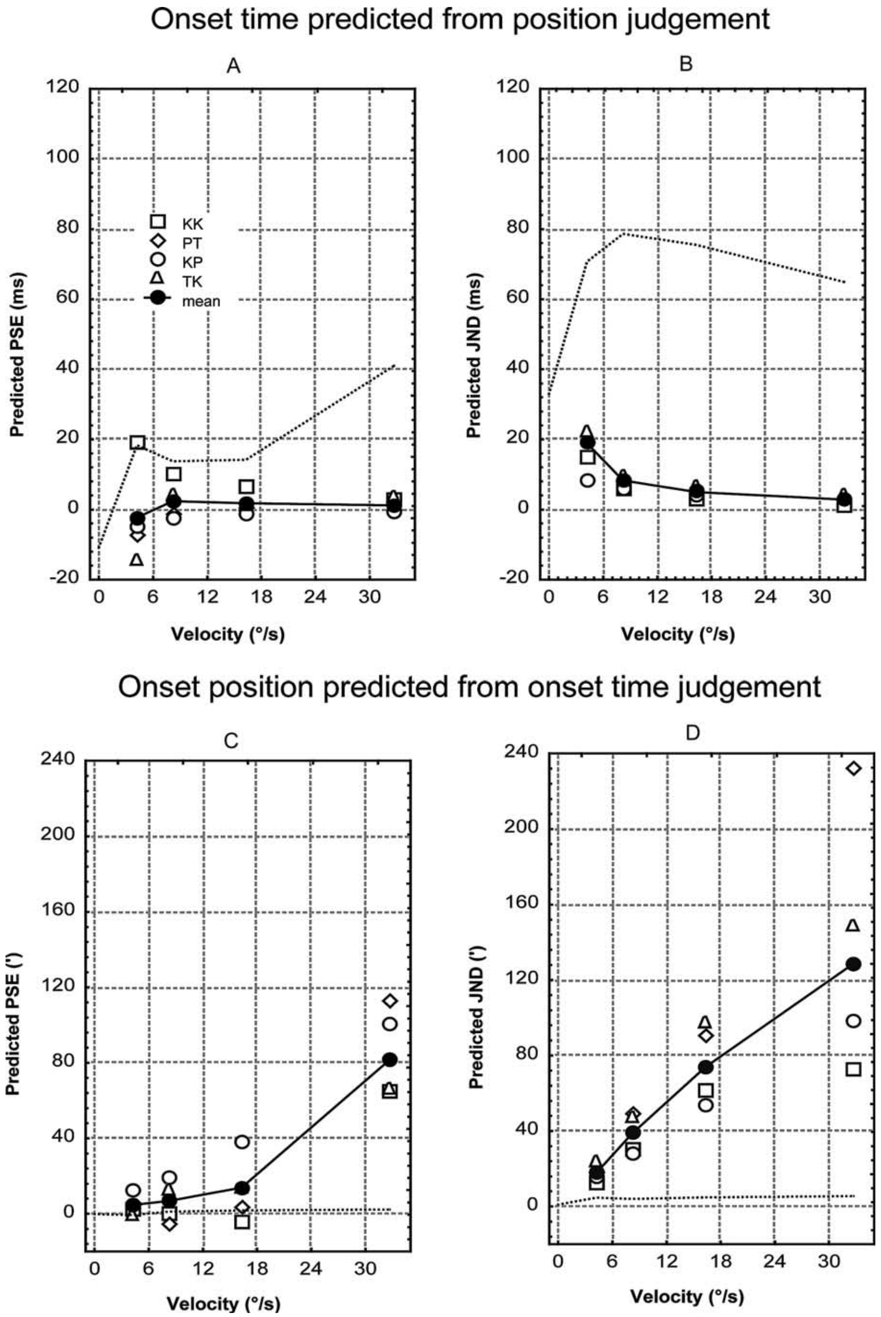

Fig. 3. Predicted occurrence moment (A) and position (C) and respective predicted discrimination ability (B, D) for the moving bar. Line graphs represent averaged data for four observers together and scatter-plots refer to individual data ($n = 60$). For better comparability, graphs A and B share the ordinate scale values with A and B but observe the difference for C and D. Dotted line plots are experimentally measured averaged values (same as Fig. 2).

task's "stop-go" movement) in four velocities with repeated measures ANOVA. The analysis revealed that the velocity had influenced the means ($F_{3,9} = 7.65$; $p = 0.008$) but the two types of movement, "go" and "stop-go", did not differ from each other ($F_{1,3} = 0.19$; $p = 0.694$). No interaction between the velocity and the movement type was detected ($F_{3,9} = 0.87$; $p = 0.490$). The LSD test confirmed that the highest velocity (32.7°/s) condition revealed of the significantly bigger FLE than all lower velocities that did not differ from each other. Consequently, the sudden appearance of the moving bar in the original timing experiment did not mask or disturb the movement perception in some other way.

5. General discussion

The main result from our study is that the perceived initial position of the moving bar is not identical to its perceived time of appearance. The onset position of a moving stimulus was judged correctly without any considerable perceived shift neither towards or opposite to the movement direction. Instead of the formerly known FE, we observed another kind of misperception in the timing task: the perceived time of the movement onset was misjudged and was judged to start up to 40 ms earlier compared to the probe. The lack of the FE in the localization task but the presence of the FLE in the timing task (most clearly at high velocities) for the same bar indicates that these two effects are most probably not caused by a single mechanism.

The first question, of course, is why the FE and FLE (at least at lower velocities) were not found in this study? Even in the worst case, the precision of position judgments was accurate enough to discover the perceived shifts in the location smaller than 6′ of visual angle. The nice and reliable FLE revealed itself not earlier than at the highest used velocity (32.7°/s). Also JNDs for the measurements were relatively large as compared to the PSEs (see Fig. 2) which suggests that there was no real constant error in the measurement. One possible reason for the discrepancy between the present and many previous studies is the stimulus design. Classically, the FE is observed in the conditions where the moving object appears from behind the edge of an occluding object. In the current study, there was no edge and the whole object appeared on the screen and started to move in one of the directions. Another likely reason is the size and the retinal location of the test stimuli. Compared with the usual size of stimuli used to produce either the FE or FLE, the dimensions of the moving and the probe bar used in this study were comparatively small. One of our reviewers drew our attention to the fact that in our experiments the moving target was relatively thin (0.16°) which is different from most previous FE studies. Our preference for a thin line was motivated by two main reasons. First, a wide bar has two edges that can be processed separately (cf. Marr, 1982) which may cause a confusion about which of them to use for localization. Second, when the width of a bar is narrow enough its position is determined by the centroid of its light distribution (Watt, Morgan, & Ward, 1983; Westheimer & McKee, 1977). However, the width of our test stimuli was nothing exceptional because both effects (the FE and FLE) have been obtained also with small dots (e.g., Baldo et al., 2002; Müsseler et al., 2002) or thin lines (e.g., Brenner & Smeets, 2000; Khurana et al., 2000). Therefore it seems unlikely that the width of the stimulus was a critical condition for the lack of displacement.

One of our reviewers noted that one aspect differentiating between different velocity conditions was the step size that was taken by the moving test bar in each video frame. The next position exceeds the bar's width only in the highest velocity condition. Might this be the reason why the FE was not observed and the FLE was present only in the 32.7°/s condition? Again, it is a very unlikely reason for the absence of the FE and the occurrence of the FLE only at higher velocities. Both effects were repeatedly observed in conditions where the width of the moving stimulus was considerably larger than that in the current study.

There is another important difference from previous studies. Instead of a short flash, all judgement were made with the reference to a probe which appeared at a certain moment and stayed on the screen for at least 800 ms if the observer's response did not come earlier. The only condition where the FLE was observed in the current experiment, was the highest velocity of 32.7°/s when it took only 228 ms to reach the edge of the screen. However, in that case the duration of the probe was prolonged by 800 ms. Nevertheless, all 4 subjects reported the FLE: the onset of the probe was delayed in order to perceive it simultaneously with the onset of the moving stimulus.

Is it possible that attentional demand is responsible for the dissociation of temporal and spatial judgement tasks? It has been argued that the attentional load is larger in the spatial judgement task than in the temporal judgement task (Posner, 1995). We may estimate it by the pair-wise (i.e., spatial vs temporal task) comparison of JNDs at different velocities. The wider the psychometric function was (and the bigger was the JND), the more attention-demanding (or complicated) the task had been. As it is clearly seen in Fig. 3, the temporal resolution had been much more inaccurate than the spatial discrimination.

One parameter that was not varied in the experiment was the eccentricity. Mostly these effects have been measured in more peripheral locations than we did. It is unknown whether the effects, the FE and FLE, are equally well present at the central vision as they are in the periphery. There are some data showing that the FE is relatively independent on eccentricity, when it is less than 9.5° (e.g., Lappe & Krekelberg, 1998; Müsseler & Aschersleben, 1998). Consequently, the effects should have appeared.

Another important variable controlling the magnitude of the both effects, the FLE and the FE, is velocity. It is not only logically expected but empirically demonstrated that the magnitude of both effects diminishes with the decrease of velocity (e.g., Aschersleben & Müsseler, 1999; Krekelberg & Lappe, 2000; Mateeff, Bohdanecky, et al., 1991; Müsseler & Aschersleben, 1998; Nijhawan, 1994). At relatively low velocities, less than 20°/s, the reported initial position of a moving object can be even reversed in the direction opposite to motion (Hubbard & Motes, 2002; also called the *onset repulsion effect* by Thornton, 2002). Although velocities (at least two higher ones) used in this study were high enough to observe the FE, we observed only minor shifts in terms of the absolute localization errors. Three observers out of four showed even some opposite mislocalization (PT, KP, TK, Fig. 2C). We do not have a good explanation for these differences. Our study is not the first one to show similar individual variability (cf. Baldo & Klein, 1995; Krekelberg & Lappe, 1999; Lappe & Krekelberg, 1998) but no clear interpretation of them has been provided. No qualitative breakpoint comparable for the 20°/s in the FE is defined for the FLE. Our data indicate that something happens between the perception of timing of objects moving at the velocity of 16.3 and 32.7°/s, too.

Whatever the reason for the lack of the significant FE in the present study is, one of the main findings of this study is a clear asymmetry between the perceived time and position of the movement onset. The precision of timing judgments was relatively poor in comparison with the spatial position judgments (see Fig. 3). The observed differences, however, may not indicate two fundamentally different underlying mechanisms but a considerable (much larger than was previously thought) variability of these two phenomena. The simple single mechanism for the FLE and FE (Eagleman & Sejnowski, 2000a, 2000b, 2000c) appears to be unsupported.

Current results seem rather to support Nishida and Johnston's (2002) conclusion that the visual system is relatively imprecise in the assessment of the temporal order of visual events. This means, in particular, that unlike physical variables we cannot automatically convert the perceived time intervals into the perceived distance and the perceived spatial phase into assumed temporal delays (cf. Baldo & Klein, 1995; Kirschfeld & Kammer, 1999; Nijhawan, 1994; Purushothaman et al., 1998; Whitney, Cavanagh, et al., 2000; the practice that is criticized also by Eagleman & Sejnowski, 2002). Although in the scaling experiments, it is often possible to present the apparent velocity as a fraction of the subjective distance and the subjective time (so called Brown's law, cf. Mashhour, 1964) it does not extend automatically to the relation between estimated instant location and time. Research also shows that psychological space and time are not judged independently: judgments about time are often influenced by the spacing of stimuli, and spatial judgments are influenced by their timing (cf. Collyer, 1977; Jones & Huang, 1982). The interdependence of judgements about space and time is another constraint of the visual system, which makes the derivation of the hypothetical space or time lags from judged location and timing respectively unwarranted. At the same time, also the idea of sophisticated position assignment and more exact relative timing in the visual system (Brenner & Smeets, 2000; Eagleman & Sejnowski, 2000a, 2000b, 2000c) remains unsupported in our experiments.

To conclude, the results of this study demonstrated that the visual system is not particularly adapted for the estimation of the temporal order of visual events but can manage satisfactory with position assignments. Whenever it is possible, the information about the temporal order is substituted with some other information supplied by other perceptual mechanisms like the detection of the movement direction (cf. Allik & Kreegipuu, 1998).

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