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The location of overt attention affects the bias in acceleration perception: A preliminary study[#][*]

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Abstract: Visual attention affects spatial and temporal processing of stimuli and consequently also affects motion perception. This study examined whether directing overt attention to different positions in the visual field affects the perception of motion acceleration. A square target travelled horizontally across the computer screen, from left to right or from right to left. Distance and duration of motion were varied. Throughout the trial, overt attention was directed to the leftmost part, to the centre, or to the rightmost part of the travelling path of the target. During the course of motion a control digit was presented at a fixated location. Participants had to identify the digit and assess how velocity of the moving target changed with time. The results showed that directing attention to different positions had an effect on acceleration perception, and that the magnitude of this effect increased with the length of the path. When attention was directed to a position that corresponded with the beginning of the path, perceived velocity of the moving target decreased with time. When attention was directed to the end of the path, perceived velocity of the moving target was constant or slightly increased with time. Different explanations of the bias in acceleration perception and its change due to fixation location are offered. Results are discussed within the context of change in target eccentricity, functioning of attention (through the formation of an object file, the perceptual acceleration, and the spatial distribution of attention), and temporal dynamics of the functioning of the motion detectors network.

Key words: motion perception, acceleration perception, visual spatial attention, eccentricity, perceptual acceleration

Vpliv mesta osredotočanja pozornosti na pristranost zaznavanja pospešenosti: preliminarna raziskava

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Povzetek: Vidna pozornost vpliva na predelavo časovnih in prostorskih značilnosti dražljajev ter posledično tudi na zaznavanje gibanja. V raziskavi smo preverjali, ali usmerjanje pozornosti na različna mesta v vidnem polju vpliva na zaznavanje pospešenosti gibanja. Na računalniškem zaslonu smo predvajali kvadratno tarčo, ki se je gibala od leve proti desni ali obratno. Spreminjali smo trajanje potovanja in razdaljo, ki jo je morala tarča prepotovati. Udeleženci so ves čas prikaza usmerjali pozornost na določeno

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točko v vidnem polju, in sicer na skrajno levi del, na sredino ali na skrajno desni del tarčine poti, kjer se je med gibanjem tarče prikazala kontrolna številka. Številko so morali identificirati in hkrati oceniti, kako se je spreminjala hitrost gibanja tarče. Rezultati so pokazali, da usmerjanje pozornosti na različna mesta v vidnem polju vpliva na zaznavanje pospešenosti gibanja in da se vpliv veča z večanjem prepotovane razdalje. Ko je bila pozornost usmerjena na točko začetka gibanja, se je zaznana hitrost gibajoče se tarče s časom manjšala, ko je bila pozornost usmerjena na točko konca gibanja, pa se je zaznana hitrost s časom večala ali je ostala nespremenjena. Spreminjanje zaznane hitrosti s časom in vpliv začetne fiksacije na zaznavo poskuša prispevek razložiti s časovnim spreminjanjem ekscentričnosti gibajoče se tarče, z značilnostmi pozornostnih procesov (z oblikovanjem datotek o predmetih, pospeševanjem zaznavanja in s prostorsko porazdelitvijo pozornosti) in s časovno dinamiko odzivanja mreže detektorjev gibanja.

Ključne besede: zaznavanje gibanja, zaznavanje pospešenosti gibanja, vidna prostorska pozornost, ekscentričnost tarče, pospeševanje zaznavanja

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Human observers do not perceive acceleration of the moving target accurately. Acceleration perception is biased. Smoothly accelerated motion is generally responded to as if the velocity were constant (Gottsdanker, 1956) and thresholds for detecting acceleration are substantially higher than thresholds for detecting deceleration of horizontal motion (Calderone & Kaiser, 1989; Gottsdanker, 1961; Schmerler, 1976). Runeson (1974) reported that motion having constant velocity was perceived as motion with two qualitatively different phases: the velocity was perceived as higher at the beginning of motion, but later on suddenly decreased. Perceived constant velocity occurred when the physical motion had begun with a certain amount of acceleration, which had later levelled off to a constant velocity. This held both for vertical and horizontal movements.

The discrepancies between physical and perceived velocity might influence the results of various studies of motion perception (e.g., velocity discrimination studies, velocity scaling studies), so it is important to study them in detail, examine why they occur, and to learn more about their underlying physiological and perceptual mechanisms.

What are the possible reasons for the bias in acceleration perception? Runeson (1974) proposed that the results of his study imply the existence of the perceptual concept of velocity. It is characteristic of natural movements which include the starting (and the stopping) phase that initial acceleration is followed by smooth transition to constant velocity. Being frequently exposed to seeing such movements, people form the perceptual concept of velocity, which has higher ecological relevance than the objective physical velocity.

However, the perceptual concept of velocity cannot explain the bias in acceleration perception entirely. For example, the magnitude of the bias in acceleration perception also depends on duration of movement: the bias is larger when motion duration is longer than when motion duration is short (Poljanšek, 2001, 2002). Velocity perception also depends on the location in the visual field to which the gaze is fixated: A moving object seems to speed up when approaching fixation and to slow down when receding from it (Cohen, 1964). It has been found that if a stationary point is fixated, perceived velocity of a moving object depends on the object's eccentricity, i.e. the object's distance from the fovea (Johnston & Wright, 1986; Tynan & Sekuler, 1982). Spatio-temporal processing in central and peripheral vision is different (see e.g. Johnston & Wright, 1983; McKee & Nakayama, 1984). Although peripheral temporal sensitivity is nearly equal to foveal temporal sensitivity (McKee & Nakayama, 1984; Watson, 1986; Waugh & Hess, 1994), the spatial grain of the visual system decreases with eccentricity. This is reflected in the corresponding decrease in different sensitivity parameters with eccentricity: the decrease in spatial frequency sensitivity (Hilz & Cavonius, 1974), contrast sensitivity (Rovamo, Leinonen, Laurinen, & Virsu, 1984), and perceived velocity (Johnston & Wright, 1986; Tynan & Sekuler, 1982). It is reasonable to expect that in situations where a stationary object is fixated, perceived velocity of object moving linearly in the periphery will change with time due to the change in its distance from the fovea. However, in Runeson's (1974) study, where observers pursued the moving spot with the gaze, target eccentricity did not change with time. Factors other than eccentricity must have caused the bias in acceleration perception. Although the presence of other objects in the visual field (e.g., boundaries, fixation points) might be an important determinant of the perceived velocity of a moving object (Cohen, 1964; Michotte, 1963), in Runeson's (1974) experiments either no such objects were present or the bias in acceleration perception was found both in the condition where the target travelled across the stationary background pattern and in the condition with no background.

Runeson (1974) reported that the event in the beginning of target motion is "special, somewhat peculiar" (p.17), and that sometimes observers cannot see what happened in the beginning of motion. Gottsdanker (1961), analogously, characterised the findings of his study as the consequences of "missing" the start of the motion, because the difference in accuracy of identifying accelerated and decelerated motion diminished when he used a lead-in motion before the start of the portion to be judged. The reports that the very beginning of motion is qualitatively different from the rest of motion led us to consider another possible explanation of the bias in acceleration perception: the in-stream perceptual acceleration hypothesis. This hypothesis which emphasises the attentional modulation of motion perception was introduced by Bachmann (2001) to explain other motion perception phenomena. We suspect that attention might also modulate the perception of acceleration of a moving target.

Attentional modulation of motion perception

Visual attention guides selective processing of stimuli and controls the access to conscious experience (Hatfield, 1998). Although we usually direct attention to visual stimuli whose projections fall in or closely around the fovea (i.e., attention is determined by our gaze, and this is referred to as overt attention), we can also pay attention to a location far from fovea and move attention independently of gaze. Such an orienting of attention, which is not associated with head and eye movements, is referred to as covert attention. It was shown previously that human observers are able to track moving objects covertly with their eyes fixated at a different, static point (Pylyshyn, 1998; Shioiri, Yamamoto, Kageyama, & Yaguchi, 2002).

Visual attention modulates the perception of both static (Bashinski & Bacharach, 1980; Egly & Homa, 1984; Stelmach & Herdman, 1991) and moving stimuli (Raymond, 2000; Watanabe & Miyauchi, 1998). The processing of static stimuli at the place where attention is focused differs from the processing of stimuli in other places of the visual field, and this was demonstrated both with the overt attentional focusing (Stelmach, Herdman & McNeil, 1994) and the covert attention (Bashinski & Bacharach, 1980; Yantis, 1998). Attention can influence the processing of spatial as well as temporal characteristics of stimuli. At the location to where covert attention is directed, spatial resolution of visual patterns improves compared to the non-attended locations (Carrasco, Williams, & Yeshurun, 2002; Downing, 1988) and the identification of a stimulus is faster (Juola, Bouwhuis, Cooper, & Warner, 1991; LaBerge, 1983; LaBerge & Brown, 1989). Stelmach and Herdman (1991) showed that directing attention to a certain part of visual field affects the temporal characteristics of stimulus processing. They found that if two static objects were briefly and simultaneously presented, one located at attended and the other at non-attended location, observers reported of anisochronous presentation of both stimuli. The object that appeared at the attended location was perceived to occur earlier. Based on these findings they proposed that visual response to the object that receives attention becomes more brisk and that attention enhances the transmission speed of visual information in the sensory-perceptual system. Mattes and Ulrich (1998), who studied the effects of attention on temporal processing, arrived at a similar conclusion after they had found that active attending to a certain stimulus extends its perceived duration. They speculated that the temporal frequency of an internal clock increases with attention. Consequently more impulses are detected within a given unit of objective time, causing the duration of the attended stimulus to be perceived as longer. Congruently with this, we might expect that perceived velocity of a moving object will be lower when the object is overtly attended than when it is not. Indeed, if we track a moving object against a stationary background it appears to move more slowly and make a smaller excursion than if we fixate on the background while the object moves (Cohen, 1964), which is referred to as the Aubert-Fleischl phenomenon (however, it is usually explained with eye movement induced changes in the thresholds for motion; see e.g. Wertheim, 1994).

Dynamics of attentional modulation and the perceptual acceleration

Attentional facilitation is not instantaneous. It takes time for attentional mechanism to maximise its facilitative modulating effect on specific encoding process (Bachmann, 2001), for instance, on encoding of stimulus position. There is evidence that in the first 100-200 ms after attention has been directed to a certain object, object's position is not encoded accurately. For example, Suzuki and Cavanagh (1997) reported that perception of the position of a suddenly presented probe is distorted (i.e., repulsed from the locus of attention) in the first moments of presentation. In their study, a cue which captured covert attention was presented in the visual field. A subsequently presented probe (vernier stimulus) appeared displaced away from the focus of attention in the first 200 ms of the probe exposure, but later the initially distorted representation of position was replaced by a more accurate representation, presumably because attention became focused around the probe.

Bachmann (1999, 2001), furthermore, described a variety of perceptual phenomena involving motion (the Fröhlich effect, the effect of overtaking, the flash-lag effect, etc.) which seem to prove that the nature of attentional modulation is dynamic. For example, the Fröhlich effect (Aschersleben & Müsseler, 1999; Müsseler & Aschersleben, 1998) occurs when a moving target suddenly appears in the visual field from behind an opaque occluder. The perceived position of target appearance is displaced in the direction of motion: The first perceived position of the target is not the actual position of appearance but some later position. Bachmann and his co-workers (Bachmann, 2001; Bachmann, Luiga, Põder, & Kalev, 2003) set the hypothesis of in-stream perceptual acceleration to explain the Fröhlich effect. They claimed that the process of attentional modulation of signals that carry the information about stimulus spatial position takes some time to become effective. At the moment when the modulation becomes effective, the characteristics of spatial position of the stimulus have already changed, indicating an advanced position in space.

The in-stream perceptual acceleration hypothesis (Bachmann, 2001; Bachmann et al., 2003) states that streamed input signals are sampled and their processing, if modulated by attention, ultimately reaches the stage of explicit (conscious) representation of the stimulus-object or event in its specific form in subject's awareness. When stimulation is temporally extended, the latency with which the samples become explicitly represented is not invariant. During the first moments after the target appears in the centre of attention, the speed with which samples of perceptual information become represented in explicit format is relatively low, but progressively the speed increases and reaches a stabilised value after about 100-200 ms. Bachmann (2001) called this early phase of the processing of attended stimulus the phase of perceptual acceleration. The theory of perceptual retouch (Bachmann, 1999; Bachmann et al., 2003) helps explain the perceptual acceleration effect. For a moving stimulus, where spatially adjacent replicas of the stimulus are sampled successively in time, the first few stimulus replicas as the input initiate two neural systems: (i) specific cortical neurones that process a certain stimulus feature, e.g. its location, and (ii) a thalamo-cortical modulation system which modulates the activity level of the cortical units. As this modulation takes some time to become effective, the latency for an explicit representation of the first replicas is long. However, by triggering the modulation system the preceding signals cause the following signals to be processed faster and faster. Sampling of the signals, which is initially slow, accelerates with accumulating stimulation. When the phase of the perceptual acceleration is over and the encoding speed is stable, detailed coding of object's characteristics (e.g., its position, shape, colour) can take place fast. Therefore, the processing of an object showing up in the visual field is in the first moments quite different from the processing of an object that has already been present in the visual field for some time, attended and effectively processed. According to Bachmann (2001), "... the spatiotemporal properties of explicit perception should be different between the conditions where the signals of a stimulus-event have been just onset and the conditions where these signals have been accumulating already for some time." (p. 212). We would expect that spatio-temporal characteristics of an object in motion will in the first moments of its appearance not be processed correctly, or at least they will not be processed equivalently to characteristics of moving objects that had already been present in the visual field for some time.

Perceptual acceleration as a possible source of the bias in acceleration perception

In light of the hypothesis of the in-stream perceptual acceleration (Bachmann et al., 2003), we will try to explain the bias in acceleration perception with changes in the speed of processing of visual information that occur over time. In the first few moments after target appearance, accurate information about target location is absent and, accordingly, target velocity might not be processed correctly. Velocity overestimation might be a consequence of the change in the speed of information transmission in the visual system. According to Bachmann (2001), in the first few moments after object's onset the speed of information transmission is low. Despite the subsequent change in object's position, attentional modulation of position processing can take effect because (i) motion is usually predictable (Bachmann, 2001) and because (ii) the object can be successively tracked by attentional mechanism, even without eye-movements (Pylyshyn, 1998; Scholl and Pylyshyn, 1999). With time, as the object is attentively tracked, the speed of sampling for explicit representation increases. As a consequence, the encoding of position, which is slow at the beginning, becomes faster and faster, until it finally reaches an optimum speed. Let us assume that the sensory system samples target position in equal temporal intervals. Due to the attentional modulation the explicit representation of the next positions of the target will be formed with progressively smaller latencies. Therefore, the changes in the explicitly represented positions will be rapid in the beginning of motion and slower later on. Consequently, the perceived velocity (speed of changing target position) will decrease with time. At first, perceived velocity will be overestimated, but when the perceptual acceleration phase is over it will be perceived accurately.

Runeson (1974) reported that overt attending to the location of target appearance did not completely eliminate the bias in acceleration perception. Comparably, Müsseler and Aschersleben (1998) found that the Fröhlich effect was smaller when observers covertly directed their attention to the location of target appearance before it had actually appeared, but the effect did not disappear completely. These findings indicate two important things. The fact that attending to the location of target appearance did not completely eliminate the two effects could indicate that the processing of motion is not yet efficient in the first moments after its onset, no matter where in the visual field attention is directed. This is what we have just explained with the perceptual acceleration. Second, there was a difference in the magnitude of the Fröhlich effect and in the magnitude of the bias in acceleration perception between the condition where attention was directed to the location of target appearance and the condition where attention was not directed to the location of target appearance. We could speculate about the implications of these findings. The difference might show that the perceptual acceleration was different in the two conditions. The larger effect obtained in the condition where the target appeared in an unexpected position might show that in this condition the phase of the perceptual acceleration was longer and that it took longer for attentional modulation to become effective. This might be related to the preparatory effect of attention. According to the gradient model of spatial attention (LaBerge, 1995; LaBerge & Brown, 1989) which assumes that the facilitatory effect of attention on stimulus processing is largest at the place where attention is directed but gradually drops for distant locations, we might expect that the distance of the position of unexpected target appearance from the attended location might affect the bias in acceleration perception. We propose that if attention is affixed to the location of target appearance prior to target onset, attentional modulation system might already be triggered (which is synonymous with the preparatory attention). For example, the connection between the location map (see Treisman, 1998) and the thalamocortical modulation system might be established, which might increase the speed of the perceptual acceleration within various feature maps (Treisman, 1998) activated after the target actually appeared at the attended location. As a result of that, the perceptual acceleration would be faster at the previously attended location than at the previously non-attended location. Congruent with this speculation is the evidence that the further the target is from fixation, the longer it takes for covert attention to be shifted to the target (Egly & Homa, 1991; Shulman, Remington, & McLean, 1979; Tsal, 1983; but see Sperling & Weichselgartner, 1995, for the finding that attention shift time is independent of shift distance). We could further speculate that the larger the distance between the attended location and the location of the suddenly appearing target, the slower the perceptual acceleration and, consequently, the larger the effects arising from attentional modulation of target processing, such as the Fröhlich effect and the bias in acceleration perception.

To summarise, directing attention to a certain location in the visual field affects the processing of spatial and temporal properties of stimuli. Measurable characteristics of the speed of processing depend on the location and duration of directing attention. We therefore expect that directing attention to different places in the visual field would also affect the perception of velocity and the perception of change in velocity of a moving object. In the present study we tested this assumption. We examined whether object's acceleration will be perceived differently in situations where overt attention is directed to the location of object's first appearance (to the beginning of motion) and in situations where overt attention is directed to other locations in the visual field (to the location in the middle of travelling path and to the location at the end of it). We also controlled the potential effect of the distance between fixation and the location of target appearance. We therefore investigated how fixating different parts of the paths having different lengths affects the perception of motion acceleration.

It is important to say that fixating (or directing overt attention to) a stationary point on the travelling path of a moving object necessarily correlates with target eccentricity. When the point of the object's first appearance is fixated, the object's eccentricity increases with time as the object moves along the path. Correspondingly, when the point of the object's disappearance is fixated, the object's eccentricity decreases with time.

If the eccentricity were the only important factor determining velocity perception, we would expect perceived velocity of the object moving away from the fovea to decrease with time and perceived velocity of the object moving toward the fovea to increase with time. If in both conditions the object traversed the same distance, we would also expect the amount of change in perceived velocity in both conditions to be equal, but with an opposite sign (see the dashed lines in Figure 1). Because traversed distance is related to the amount of change in target eccentricity, we would expect the amount of change in perceived velocity to increase with increase in traversed distance.

If, on the other hand, the perceptual acceleration hypothesis were also valid, the symmetric changes in perceived velocity for motion away and toward the fovea would no longer be observed. The solid lines in Figure 1 schematically show how perceived velocity might change with time due to the combined effect of the perceptual acceleration and the change in the eccentricity of the moving target. For motion away from the fovea, a large decrease in perceived velocity with time would be expected. In the first moments after motion onset velocity would be overestimated, but later on perceived velocity would decrease due to the perceptual acceleration and due to the increase in target eccentricity. The larger the change in target eccentricity, the larger the expected decrease in perceived velocity. For motion toward the fovea, the perceived starting velocity of the peripheral target would be higher than expected from target eccentricity only, because of initial non-optimal speed of information transmission. Later perceived velocity would decrease due to the perceptual acceleration. Because overt attention would not be directed at the location of target appearance, the decrease in perceived velocity would be slower and would take more than 200 ms. It would also be neutralised somewhat by the decrease in target eccentricity (which would cause perceived velocity to increase with time). If perceived velocity ambiguously changed with time (i.e., a decrease were followed by an increase; see Panel B in Figure 1), perceived velocity would probably be estimated as approximately constant throughout the trial. If the dynamics of the perceptual acceleration really did change with eccentricity, then motion distance would affect the magnitude of the change in perceived velocity.

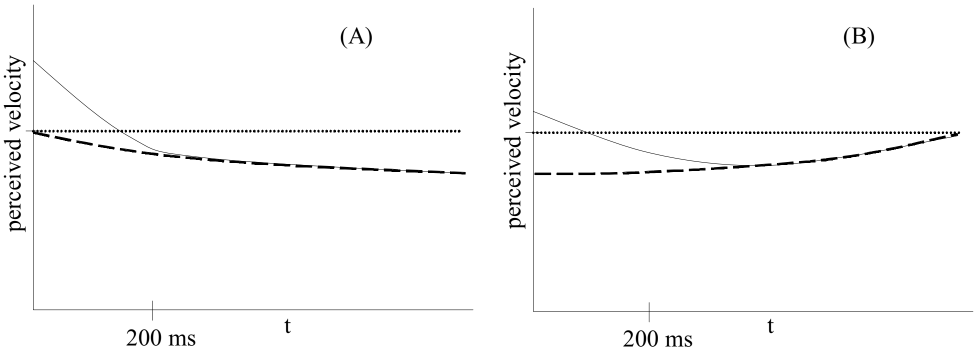

Figure 1. A schematically shown expected change in perceived velocity of the target moving away from the fovea (Panel A) and of the target moving toward the fovea (Panel B). Horizontal dotted lines show the objective velocity. Dashed lines show the expected effect of the change in target eccentricity on velocity representation. Note that the effect of the change in eccentricity for motion away from the fovea is exactly the opposite of the one expected for motion toward the fovea. We assume that perceived velocity of the moving target (solid lines) is relatively high in the first moments after motion onset, but then decreases due to the perceptual acceleration. Once the perceptual acceleration phase is over, perceived velocity is affected mainly by the change in target eccentricity.

Method

Participants

Nine observers (3 male and 6 female, aged 21 to 28, all with normal or corrected-to-normal vision; one of them was the first author of this paper A. P., others were undergraduate and graduate psychology students) volunteered to participate in the experiment. Three participants had previous experience with experiments in acceleration perception. Except A. P., no participant had knowledge about the purpose of the experiment[1].

Apparatus and stimuli

Stimuli were generated on DELL Latitude CS computer (with Intel Pentium II 128MB RAM processor and NeoMagic MagicMedia256ZX graphic accelerator). The MS Visual Basic 6.0 application included the HiTime VBX/OCX control (Mabry Software Inc.), which gave access to accurate time control of stimulus generation. Stimuli were presented on CRT display NOKIA Multigraph 446XPRO with 85-Hz vertical refresh rate and phosphor P22.

A blue square (with 2 cd m^{-2} luminance), which subtended a visual angle of 0.4°, was presented on a homogeneous grey background (with 29 cd m^{-2} luminance). Target changed its position in small discrete steps rapidly, so that motion was perceptually continuous. Motion can be described by the equation

$$s_i = v_0 t_i + \frac{1}{2} a t_i^{\,2}, \tag{1}$$

where s_i stands for target position (travelled distance) at the moment t_i. Motion acceleration is denoted by a and the starting velocity by v_0. The starting velocity was determined from

$$v_0 = \bar{v} + a \frac{\bar{v}}{2}, \tag{2}$$

where the average velocity $\bar{v}$ was calculated according to (i) the total distance and (ii) the time needed for traversing that distance.

A black paper mask surrounded the visible region (33.5 cm horizontally × 25.0 cm vertically) on the computer screen. In the centre of the grey screen two narrow vertical lines, lighter grey than the background, were presented as the borders of the area where the target was visible during its travel. The horizontal distance between the vertical lines varied as a function of motion distance. A light-grey fixation point, subtending a visual angle of 0.2°, was presented in the centre of the screen. Whereas its vertical position was fixed (in the middle of the screen height), its horizontal position was variable. It was presented (and centred) either on the left vertical line, in the centre of the travelling area, or on the right vertical line. In order to control the overt attention, participants had to gaze at the fixation point throughout the trial and recognise digit probes presented from there.

At the beginning of the trial, the fixation point turned yellow for 200 ms. The change in its colour automatically pulled the attention (and gaze) towards it. One second later the trailing edge of the vertically centred blue target appeared on the screen. Due to the accretion of target's trailing edge the target appeared to gradually emerge from behind one of the vertical lines, it then moved across the travelling area to the border on the other side, and disappeared behind it. During its motion, after a random time interval, a red digit which subtended a visual angle of 0.3° vertically (font: Arial) and had a value varying between 0 and 9, replaced the fixation point for 100 ms. The digit was introduced as a probe-stimulus for a supplementary recognition task which allowed to ensure that within a trial overt attention was directed to a certain position in the visual field. Because participants were not certain when exactly the digit would appear, they had to attend the area of visual fixation throughout the trial.

Procedure

The experiment was run in a dimly lit room. The walls were covered by a black matte paper in order to avoid possible distractions. The distance of participants' eyes from the screen was 100 cm and the head was stabilised by head rest to maintain this distance at all times. Viewing was binocular.

The participant had to gaze at the fixation point throughout each trial, follow the target in motion by covert attention, and identify the presented digit. Five-hundred ms after the moving target disappeared, 10 buttons appeared on the screen and the participant had to identify the digit by choosing one of the presented buttons by pointing and clicking it with a mouse. If a wrong alternative was chosen, the answering procedure stopped and the trial was later repeated. If the correct alternative was chosen, the participant continued answering and had to assess how target velocity changed with time. He or she had to choose among alternative descriptions of motion: *decelerated*, *linear*, or *accelerated*[2]. If the participant did not pay attention to the trial or forgot what motion was like, she or he could choose the alternative *Once again* and the trial was repeated later. When pressing the button *Next* both answers were saved and the next trial was presented. Participants proceeded with trials as fast as they wanted, and could rest between trials. During the experiment they received no feedback about the accuracy of their responses about target acceleration.

In the experimental design four independent variables were manipulated: motion distance (4°, 8° or 16° of visual angle), motion duration[3] (1000 or 2000 ms), motion direction (to the right or to the left), and the position of directing overt attention (to the left side, to the centre or to the right side of the travelling area). There were 36 experimental conditions altogether.

To describe acceleration perception for each participant, we searched for two different values of parameter a in Equation 1. The value of a, at which in 50% of the trials the participant reported of decelerated motion and in the other 50% he or she reported of a different kind of motion, was called *the deceleration threshold*. The value of a, at which in 50% of the trials the participant reported of accelerated motion, was called *the acceleration threshold*. The staircase method was used to determine the two thresholds. In every experimental condition, two series were presented, series D to determine the deceleration threshold, and series A to determine the acceleration threshold. For all the participants, the first value of parameter a was set to –0.6 for series D and +0.6 for series A, at which motion was usually recognised as linear. In series D, the value had been reduced in subsequent steps by 0.2 for as long as the participant responded with *linear* or *accelerated*. As soon as the answer turned into *decelerated*, the value of a started to increase by 0.2 until the answer turned into *linear* or *accelerated* again. Deceleration thresholds were determined at the reversal points (as the mean between the value of a before and after the series reversal). In series A, the value of a was increased in subsequent steps by 0.2 until the participant responded *accelerated*. At that point the series reversed and the value of a started to decrease until a different answer was obtained. Acceleration thresholds were determined at reversal points. If the value of a fell below –2.0 in series D or above +2.0 in series A[4], the series was terminated and started anew at the a value –0.6 (+0.6). The series terminated after eight reversals.

Series for different experimental conditions were intermixed (64 series ran at the same time) in order to eliminate potential serial effects. Participants usually needed more than 1000 trials to finish the experiment. They were allowed to finish participating when tired and to continue on the following day. The experiment was usually completed in two or three sessions, each of which lasted approximately an hour.

For each experimental condition, thresholds for the last six reversals were averaged, and the mean of the average acceleration and deceleration threshold was calculated. The mean represented the point of subjective linearity (PSL), i.e. the value of parameter a at which the participant would most likely report of linear motion. The results of two participants which previously had no experience with related experiments had to be excluded from further analyses (because too many thresholds exceeded possible values of parameter a in equation 1). The PSLs were entered into a four-way repeated-measures ANOVA. A significance criterion of $p < .05$ was used.

Results

We shall begin with a short comment on the difficulty of the task. Usually, if the task did not include identification of digit and attentional resources were occupied in motion task only, participants would recognise cases with parameter a less than –1.0 (deceleration) or greater than +1.0 (acceleration) as motions with non-constant velocity. The digit identification clearly made the task more difficult, and two participants failed to see the largest possible acceleration.

We expected that acceleration perception would be different if overt attention was directed to different parts of target motion. These expectations were confirmed. The analysis of variance (Table 1) showed a large (and significant) interaction between motion direction and the direction of overt attention (i.e., the position of fixation point). This interaction is represented as a pattern of crossed lines in Figure 2 and can be observed at all three levels of the travelling distance variable. We can clearly see that the perception of motion acceleration (linearity) was affected by the position in the visual field where overt attention was directed. For all distances used, when participants directed their attention to the beginning of motion (to the location where the target first appeared, i.e., to the leftmost part of the travelling area when target travelled to the right, and to the rightmost part of travelling area when target travelled to the left), target had to accelerate for motion to be perceived as linear (PSL > 0.0). In other words, physical velocity had to increase with time for motion to be perceived

Table 1: Summary of ANOVA of PSLs (points of subjective linearity)

	Effects		Error			
Source of variability	*df*	*MS*	*df*	*MSE*	*F*	*p*
Duration	1	3.148	6	0.182	17.256	.006
Distance [a]	1.1	0.019	6.6	0.417	0.044	.861
Direction	1	0.550	6	0.048	11.542	.015
Position	2	0.052	12	0.079	0.651	.539
Duration x Distance	2	0.113	12	0.030	3.782	.053
Duration x Direction	1	0.049	6	0.006	8.003	.030
Distance x Direction	2	0.142	12	0.020	7.209	.009
Duration x Position	2	0.007	12	0.012	0.609	.560
Distance x Position	4	0.001	24	0.032	0.314	.866
Direction x Position	2	3.484	12	0.047	74.740	.000
Duration x Distance x Direction	2	0.070	12	0.009	7.797	.007
Duration x Distance x Position [a]	2.2	0.055	13.3	0.033	1.654	.228
Duration x Direction x Position	2	0.197	12	0.027	7.229	.009
Distance x Direction x Position [a]	1.6	0.477	9.8	0.109	4.376	.050
Duration x Distance x Direction x Position	4	0.028	24	0.015	1.857	.151

Note: The results of seven participants were analysed. Duration of motion had two levels: 1000 and 2000 ms. Travelled distance was 4°, 8° or 16° of visual field. Target travelled either to the left or to the right (direction). Participants directed their overt attention to the fixation point that could occupy three different positions: the leftmost point, the centre, or the rightmost point of travelling area.

[a] Because the sphericity assumption was not met, Greenhouse-Geisser correction was used to assess the significance of the effect of the relevant source of variability.

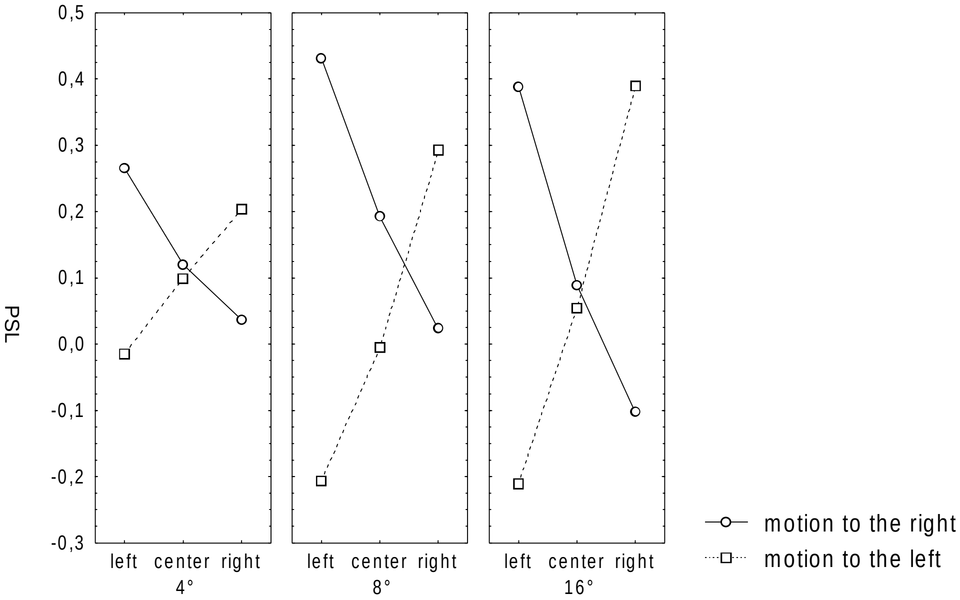

Figure 2. The effect of travelled distance, position of directing overt attention, and motion direction on the value of the point of subjective linearity (PSL). Target could travel across three different distances (4°, 8°, or 16°). The leftmost, the centre, or the rightmost part of travelling area was fixated (overt attention was directed there). Target moved either to the left or to the right. PSL is the measure that indicates target's actual acceleration that was perceived as zero acceleration. Each point represents the average PSL for seven participants within a given condition, averaged across two levels of motion duration. Positive values of PSL show that motion had to accelerate, whereas negative values of PSL show that motion had to decelerate in order to be perceived as linear, i.e. having constant velocity. The figure shows that when overt attention was directed to the beginning of the path (motion to the right – fixation left and motion to the left – fixation right conditions), the value of PSL was largely positive. When overt attention was directed to the end of the path (motion to the right – fixation right and motion to the left – fixation left conditions), negative or zero actual acceleration was perceived as zero acceleration. The effect of the location of directing overt attention on the value of PSL is therefore indicated by the crossing of the solid and the dotted line. The effect of the location of overt attention on the value of PSL was much larger when target crossed 8° or 16° of visual angle than when it crossed 4° of visual angle (see text for further explanation).

as having constant velocity, meaning that perceived velocity must have decreased somewhat with time[5]. When participants directed their attention to the end of the path (to the location where target left the travelling area, i.e., to the leftmost part of the travelling area when target travelled to the left, and to the rightmost part of the travelling area when target travelled to the right), acceleration perception was less biased. Target had to move with constant velocity or decelerate slightly for motion to be perceived as linear. This suggests that perceived velocity remained approximately constant with time or slightly increased with time. On average, when attention was directed to the middle of the path, motion had to accelerate slightly to be perceived as linear.

Figure 2 shows that the interaction between motion direction and location of directed attention varied with travelled distance (the statistical significance of this three-way interaction *Distance × Direction × Position* is shown in Table 1). In other words, the effect of location of directing attention varied with distance: this effect increased with increase in travelled distance. Location of directing attention had the smallest effect on acceleration perception in cases where motion distance was shortest. In this condition, acceleration perception (perception of motion linearity) was also closest to being accurate. When overt attention was directed to the final part of motion path, linear motion was perceived as such. For the two larger distances, the results were different. For the intermediate (8°) distance, when overt attention was directed to the final part of motion path, there was no bias for motion to the right, but

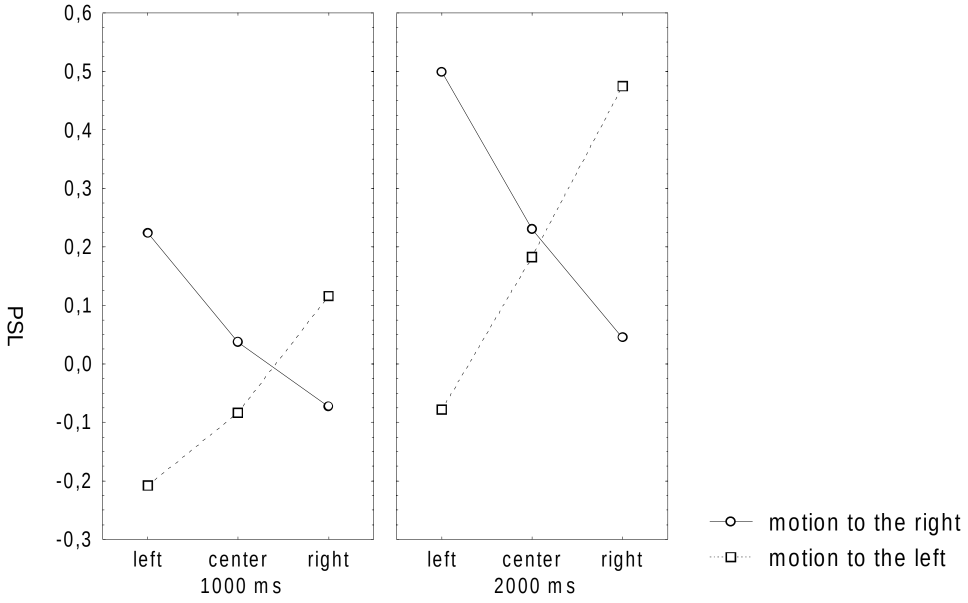

Figure 3. The interaction of motion duration with direction of motion and position of directing attention. Positive values of PSL show that motion had to accelerate, whereas negative values of PSL show that motion had to decelerate in order to be perceived as linear, i.e. as having constant velocity. At the shorter motion duration (1000 ms), the observed points of subjective linearity (PSL, i.e. actual accelerations that were perceived as zero acceleration) are symmetric around zero. At the longer motion duration (2000 ms), PSLs were higher in all the conditions: motion had to accelerate more to be perceived as linear.

for motion to the left, there was actually a bias in the opposite direction opposite from the expected: target had to decelerate for motion to be perceived as linear. For the largest (16°) distance, when overt attention was directed to the final part of motion path, motion in both directions had to decelerate in order to be perceived as linear.

In Table 1 we can also see that the effect of location of directing attention was slightly more pronounced at the longer duration of motion, as revealed by the statistically significant *Duration × Direction × Position* interaction, shown in Figure 3. In addition, the main effect of duration was statistically significant. For 1000-ms motion, the average PSL for 7 participants was 0.00 (*SE* = 0.13), and for 2000-ms motion, the average PSL was 0.23 (*SE* = 0.09). At longer duration participants reported of decelerated motion whereas at shorter duration linear motion was on average perceived as such. There was also a small, but statistically significant, difference in the magnitude of the bias in acceleration perception for the two motion directions: for motion to the right, the average PSL was 0.16 (*SE* = 0.11), and for motion to the left, the average PSL was 0.07 (*SE* = 0.11). Figure 2 shows that the motion direction effect was substantial in conditions with 8° travelling distance: When moving to the right, target had to accelerate more for motion to be perceived as linear. In conditions with the other two distances motion direction effect was, however, negligible.

Discussion

The present study provided a situation in which the observers had to divide their attention between two objects (the digit probe and the moving target) if they wanted to achieve maximum performance. Therefore, their attention was most probably not totally dedicated to one object, but was divided. Some participants reported that they had difficulties observing motion during the time the digit was presented and shortly afterwards. This may be related to the psychological refractory period (see e.g. Pashler & Johnston, 1998; cf. Shapiro & Luck, 1999). However, at the end of the experiment participants did not report of such an effect any more. It is possible that participants eventually shaped their strategy and that with learning the perceptual processing was shared between the two tasks more efficiently.

We believe that in our experiment visual fixation was synonymous with overt attention because (i) the digit recognition probe task was used to test whether fixated area was actually attended, and because (ii) in gathering data that was included in ANOVA only the trials with successful digit recognition were included. Coincidence of attention and fixation can thus be assumed for that data. To be able to assess the acceleration of the moving object, participants had to track the object by covert attention. Therefore, we propose the existence of two peaks of attentional activity in the experimental situation: one at the location of gaze and the other at the location of the target. One of the peaks of attentional activity was hence overt and stationary, and the other was covert and moved with the target. It was previously proposed that neural activity can indeed be dynamically distributed and activity can accumulate to form a number of activation peaks, which are a form of preattentive location encoding (LaBerge & Brown, 1989; Wright & Ward, 1998). Covert attention can be allocated to multiple regions of the visual field, either preattentively (Pylyshyn, 1998) or voluntarily (Bashinski & Bacharach, 1980; Egly & Homa, 1984; Juola et al., 1991), and can stay affixed to the moving object (Pylyshyn, 1998).

In our experiment, the attended location (location of the digit) was always in the foveal area and the majority of motion path lied outside the fovea, in the peripheral visual field. This introduced the eccentricity effect to our experiment[6]. We expected that the change in the distance of the moving target from the fovea (and also from the attended location) would result in some change in its perceived velocity. We proposed that certain patterns in the results of our study could indicate whether one of the reasons for the bias in acceleration perception is the perceptual acceleration.

If solely the eccentricity factor were responsible for the obtained results, we would expect accelerated motion to be perceived as linear in trials where the target departed from the attended area, because motion acceleration would just compensate for the decrease in the perceived velocity due to the increase in eccentricity. In the same manner, we would expect decelerated motion to be perceived as linear in trials where the target approached the attended area. Furthermore, for the perception of constant velocity of motion over a certain distance, we would expect the physical velocity of the departing target to decrease to the same extent the physical velocity of the approaching target increased. For example, when attending to the left part of travelling area, if obtained PSL for motion to the right was 0.3, for motion to the left the value of the PSL should be –0.3. We can see in Figure 2 that this expectation is not entirely valid. In conditions of attending to the left part of travelling area the absolute values of the PSL were not equal in "depart" (motion to the right) and "approach" (motion to the left) trials, as we would expect if the eccentricity factor were the only one effective. An analogous pattern was observed for the conditions of attending to the right part of travelling area. We can conclude that although the change in eccentricity most probably affected the PSL, eccentricity was not the only factor involved in acceleration perception.

The borders of the travelling path could also have an effect in our experiment. The target could perceptually slow down when receding from the border and speed up when approaching it (see Michotte, 1963). However, one would expect the effects of the two borders to be symmetrical and to result in an inverted sigmoid impression of velocity change. Such impressions were rare and, as stated in the previous paragraph, the absolute values of the PSL were not equal in "depart" and "approach" trials. So, the explanation based on the presence of borders in the visual field is not sufficient and will not be pursued further in this paper.

Our results indicate that both the change in eccentricity and the perceptual acceleration affected the value of the PSL, in the way that was proposed in Figure 1. Let us examine Figure 2 in more detail.

When attention was directed to the beginning of motion, PSLs were positive and high (Figure 2). The target had to accelerate for motion to be perceived as linear. These results are in accordance with Runeson's (1974) findings that directing attention to the location of target appearance does not eliminate the bias in acceleration perception. In our study, too, the bias in acceleration perception was found, even though attention was already directed to the proper location. We believe these results could be explained by the time-course of motion processing. At the time of target's first appearance the processing of its velocity might not be the same as later on. As Bachmann (2001) claimed, the processing of stimulus spatio-temporal characteristics right after motion onset is not yet optimal. With attention engaged, the processing accelerates. With time, perceptual information more rapidly reaches explicit representation. As the processing of motion signals to explicit format becomes faster, the perceived velocity decreases such that the actual motion pattern is more accurately perceived. When overt attention was directed to the location where motion ended and the target disappeared, the results were, however, different. PSLs were equal to zero or negative (Figure 2). Therefore, we conclude that the perceptual acceleration was not the only reason for the bias in acceleration perception, because if it were, one would expect to obtain positive PSLs in all conditions (perceived velocity should be overestimated right after motion onset but within the first few hundred milliseconds after that it should decrease due to the perceptual acceleration). It seems that both the change in eccentricity and the perceptual acceleration must have affected PSLs.

According to the gradient model of spatial attention (LaBerge, 1995; LaBerge & Brown, 1989) and our speculation that the speed of perceptual acceleration might depend on the location where attention is directed, we expected that the magnitude of the effect of directing overt attention to different locations in the visual field on the perceived acceleration of motion would depend on the distance between the attended location and the target. The results (Figure 2) showed that motion distance indeed moderated the effect of attention on the acceleration perception. Directing overt attention to different places had a much greater impact on the perception of acceleration of targets that crossed larger distances.

We assume that at the shortest distance overt attention was relatively efficiently distributed over the region of motion and the facilitation effect was similar throughout the travelling area. Participants were able to precisely observe a large part of motion. Attending to the location of target disappearance had similar consequences for velocity and acceleration perception as attending to the location of target appearance. In other words, directing overt attention to different places did not have a large effect if the target moved closely around the continually attended location.

We also assume that the further away from fixation was the target, the smaller was the facilitation of its processing and the more difficult it was to observe its motion. If there was a large distance between the location where overt attention was directed and the location of target appearance, the facilitation of target processing was at zero level in the beginning and the subsequent perceptual acceleration was slow. Furthermore, the negative PSLs for targets moving toward the attended location over large distances (Figure 2) might indicate that when attention was directed to the final part of motion, the usual perceptual consequence of the perceptual acceleration (i.e., the initial decrease in perceived velocity) was not manifested. Participants either neglected the initial decrease in perceived velocity, or the increase in perceived velocity at the end of the trial prevailed over the initial decrease, so that the overall perception was the one of the increasing target velocity (see Panel B in Figure 1).

When attention was directed to the location where target left the travelling area, participants might have put more emphasis on the last part of motion when forming an assessment of motion properties. In the first part of a trial, motion properties might have been more difficult to assess, because (i) the target was then distant from fovea and spatial sampling was less precise due to the worse acuity, and because (ii) the target was then outside the distribution of the overt attention. However, some attentional resources were probably still engaged at the place of motion onset, i.e. at the very beginning of motion, since, as shown by Hillstrom and Yantis (1994), the onset of a new perceptual object usually captures attention. Because participants were aware of target's presence in the visual field throughout the trial, attention must have moved along with the target. We believe that soon after motion onset an object file (see Kahneman, Treisman, & Gibbs, 1992) for the moving target was created. Even though the creation of an object file requires attention (Yantis, 1998), it most probably did not spend the entire capacity of attentional resources. According to the object-file theory (Kahneman, Treisman, & Gibbs, 1992), properties (such as position) of the object were then recorded, saved into the object file, and regularly updated. We have already proposed the existence of two peaks of attentional activity in the experimental situation: one at the location of gaze (a fixed, larger peak of overt attention) and the other at the momentary location of the target (a shifting, smaller peak of covert attention). The one at target location enabled the formation of an object file, but did not allow for the precise coding of velocity of the moving object. Nevertheless, the perceptual acceleration phase began with the creation of the object file. When the target entered the area of the fixed peak of the voluntary directed overt attention, where its acceleration could be coded more reliably, the object file for the target was already open, motion signals have been accumulating for some time, and the perceptual acceleration phase was already over. Consequently the processing of target spatio-temporal characteristics was already optimised. Thus, perceived velocity did not change (decrease) within the temporal window for which the perceptual judgement was made. Due to the small decrease in target eccentricity within the last part of the trial, slightly decelerated motion was perceived as linear when participants directed their attention to the end of the object's motion.

Combining all the effects, i.e. the effect of target eccentricity, the effect of initial overestimation of velocity because the processing was not yet optimised, and the effect of facilitated processing at attended location, we may derive the following:

(i) For motion away from the attended location, the perceived velocity was relatively high in the initial phase but later decreased. Consequently, accelerated motion was perceived as linear. At short distances, where attention was equivalently distributed over the travelling area and the change in eccentricity was small, the decrease in perceived velocity was relatively small. At longer distances, the perceived velocity decreased more because the change in target eccentricity was larger. (ii) For motion over short distances toward the attended location, a small decrease in velocity provoked by the perceptual acceleration due to attentional modulation was neutralised by a small increase in velocity that was due to gradient in the facilitatory effect of overt attention and to the decrease in target eccentricity. For the target approaching the attended location over larger distances, the initial perceptual acceleration phase was either ignored because of the low reliability of coding for the peripheral stimuli or neutralised by the large eccentricity. With motion toward the fovea, perceived velocity increased due to acuity gradient and to attentional gradient, which is why a slightly decelerated motion was perceived as linear. (iii) When participants directed their attention to the centre of the travelling area, the situation described for motion toward the fovea was followed by the situation described for motion away from the fovea. Overall, this resulted in a small decrease in perceived velocity with time, which is why slightly accelerated motion was perceived as linear.

The explanation based on the attentional modulation of velocity perception is quite complex and, we must stress, at this point still highly speculative. The combined effect of both the attentional modulation and the change in eccentricity nonetheless seems to be a viable explanation of the obtained results.

Are there any other factors that could have operated (together with the change in eccentricity) to produce the results of our study? The effect of motion duration on the bias in acceleration perception might perhaps help answer this question. The PSL values were higher in conditions with 2000-ms motion duration than in conditions with 1000-ms motion duration. A similar effect of motion duration was also observed in our previous studies on acceleration perception (Poljanšek, 2001, 2002), where we found that the PSL increased with increase in motion duration. The results of the present study confirmed that the PSL does not only depend on where overt attention (gaze) is directed, but also on factors related to temporal properties of motion. Although attentional modulation might be one of such factors, our results could also be explained differently. Poljanšek (2001) proposed that the effect of motion duration on the PSL value might be a consequence of fast adaptation of the network of motion detectors. Right after motion onset the response of transient detectors might prevail over the response of sustained detectors, but after approximately 1000 ms transient detectors might habituate and thus perceived velocity might decrease. In Figure 3 we can see that at 1000-ms duration PSLs were distributed symmetrically about zero, whereas at 2000-ms duration PSLs were distributed symmetrically about the approximate value of +0.2. This might indicate that the value of PSL was affected both by motion duration and by the change in target eccentricity. The symmetry of the pattern of lines about zero (Figure 3, left panel) might indicate that at 1000-ms duration transient motion detectors had not yet habituated and only the eccentricity factors exerted an effect on acceleration perception. The shift of the pattern towards more positive values (Figure 3, right panel) might indicate that at 2000-ms duration fast adaptation of transient motion detectors had already taken place and the effect of fast adaptation was added to the eccentricity effect. The symmetry in the pattern of crossed lines in Figure 3 might therefore indicate the eccentricity effect, and the centre of gravity of the pattern (i.e. the average value of PSLs included in the pattern) might indicate the effect of factors related to motion duration (e.g. fast adaptation of transient motion detectors). Such an explanation of our results is therefore a very serious alternative to the one based on the combined effect of the perceptual acceleration and the change in target eccentricity.

At present we cannot determine which one of the proposed temporal factors, the perceptual acceleration or the fast adaptation of the network of motion detectors, is more liable. We have to mention, though, that the phase of the perceptual acceleration should be completed in approximately 200 ms (Bachmann, 2001) and that the period within which perceived velocity decreases to its optimal value should be relatively short and should represent only a small proportion of the overall duration of our stimuli. Fast adaptation of the network of motion detectors should, on the contrary, occur over a period longer than the period needed to complete the phase of the perceptual acceleration. It should result in the overall decrease in perceived velocity if there was no change in target eccentricity.

Conclusions

We have found that gaze direction had a notable effect on motion perception, namely the perception of acceleration. The results of our experiment have shown that when overt attention was directed to the location of motion onset, motion had to accelerate to be perceived as linear. However, when overt attention was directed away from a specific target and toward some other position in the visual field, then the bias in acceleration perception for that target was reduced or reversed. We suggested that velocity perception was affected by the change in target eccentricity combined either (i) with certain temporal properties of the functioning of motion detectors, such as fast adaptation, or (ii) with attentional factors, combining the perceptual acceleration and the spatial characteristics of attention (attentional gradient).

Although our experiment was not designed to discern the different factors, we have shown that the effect attention might have on velocity and acceleration perception deserves to be explored further. In future studies, we could examine the size of attentional window to evaluate its effects on acceleration perception. To initiate a narrow window of attention, the dual-task would be similar to the one in our present study: besides monitoring acceleration, participants' second task would be to identify a single control target. To initiate a wider attentional window, the participants' second task would be, for example, to determine whether two widely spaced control targets have been the same or different, or to identify a long word (a word of 9 letters, for example). According to our previous assumptions, we would expect small effects of the position of directing attention in conditions with a wide attentional window and larger effects in conditions with a narrow attentional window.

Finally, if we could prove that attention accounts for the bias in acceleration perception, acceleration estimation task could reciprocally be used to study the dynamic aspects of attention (how its influence on other mental processes changes with time).

Endnotes

[1] The results of A. P. did not differ notably from the results of the rest of the participants.

[2] Two more alternatives were actually presented beside the three basic answers. The first additional alternative was *first decelerated – then accelerated*, and the second additional alternative was *first accelerated – then decelerated*. These two alternatives were added due to some reports of sigmoid or inverted sigmoid motion in our previous studies (see Poljanšek, 2001). However, in the present study participants rarely chose these alternatives. Because they were not consistent in their estimates (they sometimes reported of the sigmoid motion and sometimes of the inverted sigmoid motion), such answers were considered as the answer linear.

[3] If the targets move for a fixed period, the participant could be responding to variations in the average velocity, rather than to differences in the travelling distance. To obscure this average velocity cue (for it might affect estimates of acceleration; Runeson, 1974) we used two levels of motion duration, 1000 ms and 2000 ms. In our previous research (Poljanšek, 2001), motion duration affected acceleration perception, so we expected a small difference between acceleration percepts in the two duration conditions.

[4] When the absolute value of parameter a exceeded 2.0, target came into the travelling area too late or vanished too soon. In the last case, for example, when motion was decelerated and a equalled -2.0, target final velocity was zero. When motion was decelerated even more ($a < -2.0$), the target arrived at the last position before the end of motion duration and remained there for some time. However, at the last position target was already hidden completely behind the border of the travelling area and observers could not see that it was not moving anymore. Participants who did not perceive deceleration at such values would not have noticed the small differences in motion duration and would continue to 'ignore' the change in velocity. The values of a would slowly become too large and the series would probably never terminate. We have decided to terminate such a series, start it again at the starting value and to treat such occurrence as the missing value.

[5] We use the term *perceived velocity* in the Results and Discussion sections and claim, for example, that the obtained positive PSLs indicate that *perceived velocity* decreased with time, even though observers might not actually perceive that velocity of the target changed with time. The term *perceived velocity* stands for the subjective representation of target velocity. Sometimes quite large changes in the subjective representation of target velocity may go unnoticed.

[6] At this point we would like to stress that the eccentricity effect cannot be easily separated from the attentional factors, if we want attention to be directed to a certain location on the travelling path and at the same time avoid the change in target eccentricity. A possible way to control for the eccentricity effect is to present both targets, the moving target and the control one, in the peripheral visual field. However, taking into account that in the present study two participants out of nine were not able to perform the acceleration estimation tasks, we assume that directing attention to a peripheral control target would be a very demanding task on its own, and that observers would have even larger difficulties in assessing properties of the moving target.

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