Detection of colour change in moving objects: Temporal order judgment and reaction time analysis

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Abstract. The time needed to detect changes in the colouration of a single moving stimulus becomes shorter with its increasing velocity (Kreegipuu et al., 2006 Vision Research 46 1848–1855). We examined the ability to detect colour change in moving chromatic bars or sinusoidal gratings through temporal order judgment (TOJ) and reaction time (RT) tasks to test whether the effect of velocity found in a previous study is universal and holds for different tasks and stimuli. The results demonstrate that the TOJ and simple RT to the colour change of a moving grating are insensitive to stimulus velocity. Therefore, we conclude that the process of comparison of the two internal representations of external events does not have access to temporal information precise enough to estimate the exact time when something enters our subjective awareness. The motion effect on colour-change perception seems to be confined to a single stimulus that moves across the visual field, to events that contain some spatial predictability, and to tasks that reflect the time of the change relatively directly.

1 Introduction

The colour-changing stimulus paradigm introduced by Moutoussis and Zeki (1997a, 1997b) is based on the assumption that the velocity of an object does not affect the detection of colour-change in that object (Zeki et al 1991). This assumption presumes the existence of at least two types of colour detectors (one coding red and the other green) which begin responding as soon as either of them has detected the presence of the colour they are tuned to. It does not matter whether this colour belongs to a moving or a stationary object—colour-coding units are movement-blind and simply measure the presence of radiation of a particular wavelength (cf Livingstone and Hubel 1987). However, it has been found in recent studies that V4 neurons are sensitive to motion direction (Tolias et al 2005), that colour constancy improves with motion (Werner 2007), and that the detection of changes in colour depends on the velocity of the moving target (Kreegipuu et al 2006). These findings suggest that the analyses of the different qualities (colour and motion) are not completely separate in the visual system and the colour-changing paradigm may not be suitable for measuring perceptual delays in these two qualities.

Researchers seem to agree that there is no single motion-processing system and that different moving stimuli produce different perceptual experiences. From the perspective of multisystem motion theory (Lu and Sperling 2001), it is possible that the observed change in time needed for the detection of changes in colouration of moving stimuli (Kreegipuu et al 2006) is restricted to a particular type of moving object and a movement analysing system which responds preferably to this type of stimulation.

In a recent study (Werner 2007), it was clearly shown that colour constancy improved when the colour of a moving object was compared to that of a static object. Werner (2007) showed that colour constancy first increased with the speed of the test patch, reaching a maximum at velocities of $2 – 3 \text{deg s}^{-1}$ and then started to decline at higher velocities. The demonstration that human colour constancy improves when an object moves also indicates that colour perception is not motion-blind. Most importantly, Werner found that the enhancement of colour constancy was specific
to moving objects, demonstrating that reliable identification of object motion against the background motion is an important factor in inducing the enhancement of colour constancy.

The finding that motion facilitates rather than inhibits the detection of a chromatic change (Kreegipuu et al 2006) was also observed under conditions where a moving object was clearly identified against the background. However, in addition to a clear contrast with the background, the observer had certain expectations about when and where the colour change would happen. At the beginning of the movement trajectory the probability of colour change is smaller (thus spatial and/or temporal uncertainty is larger) than at the end, as the last possible position for colour change to take place is approached. If the moving object has not changed in colour by the final possible position on the screen, the change in colour is inevitable. It is well known that reaction time (RT) increases with stimulus uncertainty (Mattes et al 2002; Näätänen 1972) and it would be expected that the change in colour is detected faster when the uncertainty of the change is smaller. Indeed, our previous research (Kreegipuu et al 2006) has shown that RTs decrease with an increase in colour-change probability. However, this decrease was independent of the effect of velocity: it still took less time to detect colour change in a fast-moving stimulus than in a slow-moving or stationary stimulus, irrespective of the probability of the change (Kreegipuu et al 2006; see also Monnier and Shevell 2004).

There are two essentially different ways in which to disentangle colour changes from stimulus-uncertainty effects. One obvious way is to use a response format where the time of the response is irrelevant. We decided to use a temporal order judgment (TOJ) task, where our observers had to compare the colour-change event with a reference signal and decide in which temporal order these two events were presented. Provided that the reference signal is consistently processed the same way, independently from the changing colour of the moving object, the results of our previous study would suggest that the colour change in a faster-moving object is perceived earlier in relation to the reference signal than similar/identical change in a slow-moving or stationary object.

Another way of reducing the effect of spatial uncertainty is to use movement inside a spatially confined area instead of a single object which travels across the screen, changing its spatial position. This could be achieved by modulating the luminance distribution inside a confined area and having the distribution move at a constant velocity within this area, then having it disappear beyond the borders of the confined area. In this case, there would be no cues about the final spatial position where colour change might ultimately occur. Thus, the observer’s readiness to respond does not increase. Of course, participants may become aware that the trials do not last forever but, as the possible timing of each particular presentation considerably and frequently varies, it is unlikely that they would have such a sharp sense of timing.

In order to decouple stimulus spatial uncertainty from readiness to respond, we designed three experiments to study the influence of velocity on the perception of colour change.

In experiment 1, we presented an auditory stimulus as a reference signal with which the colour change of a moving object had to be compared. The observer’s task was to decide whether a short auditory signal was delivered before or after the change in colour in a moving object (TOJ task).

In experiment 2, we asked observers to compare the temporal order of two colour changes and decide which of them happened first (also a TOJ task, but with different stimuli than in experiment 1). Two monochromatic vertical gratings of the same spatial frequency moved with different velocities in adjacent rectangular areas on the screen. These two gratings changed colour either asynchronously or at the same time.
On the basis of our previous results (Kreegipuu et al 2006), we could expect that the colour change of a faster-moving grating would appear earlier in time than that of the slower-moving grating, even though both changes occurred at the same time.

In experiment 3, we measured the time required to detect a change (RT task) in colour of a monochromatic grating moving at different velocities (the same stimulus as that in experiment 2). Previous results with a single object suggest the time required to notice a change in colouration of a moving grating becomes shorter as the velocity increases.

2 Experiment 1
Our purpose was to examine whether the effect of velocity revealed in our previous simple RT study (Kreegipuu et al 2006) also appears in TOJ where accuracy is required, rather than is just a quick reaction. We used an invariable auditory stimulus as a reference signal with which the colour change in the moving visual object needed to be compared. Following our previous study (Kreegipuu et al 2006), it could be expected that the PSE would shift so that the apparent time of colour change would advance relative to that of the auditory signal as it increases in velocity. Since we were also interested in whether this previously revealed effect depends on the retinal or the physical velocity of the object, we set up two experimental conditions: in the ‘fixating condition’ observers were instructed to fixate upon a small cross in the middle of the screen; in the ‘tracking condition’ they were asked to track the moving object (or direct their gaze to the stationary object but not to the fixation cross in the middle of the screen). When a point in the visual field is fixated, any moving object is constantly changing its position on the retina, but tracking it enables it to keep its retinal position almost unchanged. Both conditions induce the sense of motion.

2.1 Method
The experimental setup (see figure 1) was similar to that of our previous study (Kreegipuu et al 2006), except that the task was to compare the simultaneity of two events (a colour change in a moving object and a short auditory signal).

![Figure 1. Schematic representation of the experimental setup in experiment 1. Horizontal dots (not visible during the experiment) mark the ten possible positions of the colour change of the single bar. Stimulus onset asynchrony (SOA) between auditory signal and colour change of the bar varied from 0 (simultaneous) to 225 ms (either of the two presented earlier than the other). Vertical dots mark the position where the colour change was presented simultaneously with the auditory signal (beep 1 kHz, 0.1 s).](image-url)
2.1.1 Participants. Five female observers (aged 22–24 years), three experienced and two naive, took part in the experiment. They all had normal or corrected-to-normal vision and did not report any hearing or colour-vision abnormalities.

2.1.2 Apparatus and stimuli. Stimuli were generated on an HP 19 inch monitor screen (22.08 deg × 17 deg) via a Cambridge Research Systems VSG 2/3. In order to achieve better temporal resolution (200 Hz frame rate), the spatial resolution was reduced to 186 vertical lines and 752 horizontal positions. The time needed to make TOJ was measured with an external clock from a VSG 2/3 card, accurate to within 1 ms. The luminance of black background was 1.92 cd m\(^{-2}\). The coloured stimuli were red or green rectangular bars (1.96 deg × 0.25 deg) with approximately equal luminance of 12.7 cd m\(^{-2}\) [measured by ColorCAL (Cambridge Research Systems)]. For the red bar, the L-cone contrast was 3.22 and the M-cone contrast was 0.71; for the green bar, the L-cone contrast was 1.86 and the M-cone contrast was 2.39.

Observers sat at a viewing distance of 90 cm from the screen and were instructed to fixate upon a small cross in the centre of the screen (the fixating condition) or to track the stimulus (the tracking condition); no chin-rest was used. The auditory stimulus was a 1000 Hz beep that was presented for 0.1 s, also from a distance of 90 cm. The auditory stimulus was presented through the built-in speakers in the monitor. Observers were asked to give their response after the two stimuli had been presented by pressing one of two buttons (representing “visual first” and “auditory first”) on the keyboard. The order of sessions (tracking or fixating condition) was randomised. Subjects performed 30 practice trials before the experimental trials.

2.1.3 Procedure. Each trial started with the appearance of either a stationary or a moving rectangular bar. The bar appeared at the right or left edge of the screen and started (immediately after its appearance) to move horizontally across the screen, at the velocity of either 5.9 or 17.6 deg s\(^{-1}\). The stationary and moving stimulus trials were randomised within the experimental session. In both the fixating and tracking conditions, the bar changed colour (from red to green or vice versa) at one of ten possible positions (7.4, 8.2, 9.0, 9.8, 10.6, 11.5, 12.3, 13.1, 13.9, or 14.7 deg from the starting edge) in the central third of the screen. The time from motion onset to the colour change varied from 211 to 2492 ms, depending on the colour-change location and velocity. The stationary bar appeared randomly at one of the ten possible positions and changed colour between 317 and 2509 ms after its appearance on the screen (corresponding temporally to the relevant interval for a bar moving at a velocity of 10.6 deg s\(^{-1}\)). The stimulus-onset asynchrony (SOA) between the colour-change and auditory signal stimuli varied from −225 (auditory signal occurred before the colour change) to +225 ms (colour change occurred before the auditory signal). Observers were instructed to judge which of the two stimuli, either the auditory signal or the visual signal, appeared first. The time needed to make the TOJ (answer time) was measured from the appearance of the first event (colour change or auditory signal) to when the participant pressed either of the response buttons (“visual first” or “auditory first”). Each observer performed 420 trials per condition and velocity (2520 trials per person).

2.2 Results

Responses were coded in terms of the probability of the “colour change occurred first” response, that is the proportion of reports where the change in colour was perceived before the auditory signal. A cumulative Gaussian psychometric function was approximated to empirical data points by a nonlinear estimation procedure to establish the least-square deviation between them, and the fit was calculated for each condition and velocity (fixating condition: stationary stimulus, \(r^2 = 0.93\).
velocity 5.9 deg s\(^{-1}\), \(r^2 = 0.82\); 17.6 deg s\(^{-1}\), \(r^2 = 0.82\); tracking condition: stationary stimulus, \(r^2 = 0.86\); velocity 5.9 deg s\(^{-1}\), \(r^2 = 0.89\); 17.6 deg s\(^{-1}\), \(r^2 = 0.85\).

A repeated-measures ANOVA was used for statistical analysis. The horizontal position of the psychometric function—corresponding to the classical measure of PSE—was determined by the location of 0.5 point of the psychometric function. Thus, at that SOA value both response alternatives (“colour change first” and “auditory click first”) were chosen with equal probability. Figure 2 shows averaged PSE values (vertical lines between SOA 50 – 100 ms) across all five observers for the two observation conditions (fixating in the upper and tracking in the lower panel, figures 2a and 2b, respectively) and the three different velocities (0, 5.9, and 17.6 deg s\(^{-1}\)).

Although the vertical lines marking average PSE values seem to be aligned according to velocity, so that the PSEs for the fastest velocity are closer to zero than the others,
the effect of velocity on PSEs varied significantly between observers ($F_{8,8} = 15.68$, $p = 0.0004$).

The repeated-measures ANOVA did not reveal a significant main effect of velocity on TOJs, either in the fixating condition ($F_{2,8} = 0.053$, $p < 0.949$) or the tracking condition ($F_{2,8} = 0.443$, $p < 0.657$), which means that the PSEs did not change in favour of velocity as was expected. Also, there were considerable individual differences in the PSEs between observers ($F_{4,12} = 3.51$, $p = 0.007$). A significant main effect of the task condition—fixating versus tracking ($F_{1,4} = 15.99$, $p = 0.016$) on PSEs was revealed, meaning that the PSEs (see figure 2, vertical lines) were closer to zero in the tracking condition than in the fixating condition, although there was no significant interaction in the PSEs between velocity and the condition—fixating versus tracking ($F_{2,8} = 1.06$, $p = 0.392$).

Typically of TOJ tasks, the precision of discrimination was relatively low. The individual PSE in tracking condition for stationary stimulus varied from $-4$ ms (visual stimulus must be delayed to be perceived as simultaneous with auditory one) to $+99$ ms (auditory signal must be delayed to be perceived as simultaneous with visual one), for slower-moving stimulus from $-76$ ms to $+110$ ms, and for faster-moving stimulus from $-87$ ms to $+97$ ms. In fixating condition the PSEs for stationary stimulus varied from $14$ ms to $99$ ms, for slower-moving stimulus from $-28$ ms to $77$ ms, and for faster-moving stimulus from $32$ ms to $163$ ms. The observed individual variability (total range over conditions and velocities from $-87$ ms to $163$ ms) is consistent with previous findings (Stone et al 2001), where PSE varied between $-21$ ms and $+150$ ms. As in many previous TOJ studies, there was a tendency to report the auditory stimulus earlier than the visual event when they were actually presented simultaneously (Alais and Burr 2003; Arrighi et al 2005; Hine et al 2003), although this also depends on the stimulus intensity (Allik and Kreegipuu 1998).

Taking into account the imprecision with which the temporal order of these two events were judged, the observed differences between fixating and tracking conditions were rather insignificant (see figures 2a and 2b). Consequently, the retinal velocity of the object appears to have only a minor impact on the TOJ.

Although observers did not receive any specific instructions how quickly or slowly they should give their responses, the answer times clearly depended on velocity. Like the RT in the colour-change detection task (Kreegipuu et al 2006), the answer time decreased with an increase in velocity. Figure 3 shows that the answer time for correct choices (the reported temporal order corresponded to the actual order of events) is reduced by approximately 300 ms for both experimental conditions when the velocity increases from zero to 17.6 deg s$^{-1}$. A repeated-measures ANOVA revealed a significant effect for velocity in both the fixating ($F_{2,8} = 7.48$, $p < 0.015$) and tracking conditions ($F_{2,8} = 13.59$, $p < 0.003$). There was no significant difference in answer times between viewing conditions ($F_{1,4} = 0.0013$, $p = 0.973$) and the interaction observer $\times$ velocity $\times$ condition was not significant ($F_{8,12} = 1.434$, $p = 0.177$), indicating that velocity had an effect on answer times in both conditions and that this effect did not vary between observers. There was no interaction between the condition and velocity ($F_{2,8} = 2.53$, $p = 0.141$); as can be seen in figure 3, the two curves are almost parallel. This result indicates that the presence or absence of retinal motion was irrelevant; the answer time depended on stimulus velocity even if retinal motion was compensated for with eye-tracking.

We also found that the interaction between the type of answer (“auditory signal first” or “colour change first”) and velocity was not significant ($F_{1,4} = 0.292$, $p = 0.618$), indicating that time required to make a correct response was in both cases shortened by the velocity of the moving object.
3 Experiment 2

The problem with a single moving stimulus is that uncertainty about the change in colour is linked to the spatial positions in which this change may occur. One way to decouple uncertainty from spatial position is to use stimuli that remain stationary. In this experiment we used two rectangular areas within which luminance was varied in a horizontal direction according to a sinusoidal function. These two identical vertical gratings moved with different velocities within their rectangular windows and changed in colour from red to green or vice versa. Here, observers had to compare the temporal order of two identical changes occurring in two moving gratings with different velocities.

3.1 Method

3.1.1 Participants. Five observers (one male and four females, aged 24 – 33 years), three experienced and two naive, took part in this experiment. They all had normal or corrected-to-normal vision with no reported colour-vision abnormalities.

3.1.2 Apparatus and stimuli. Stimuli were presented on the screen of a Mitsubishi Diamond Pro 2070SB monitor (frame rate 140 Hz), which from a viewing distance of 90 cm subtended 27.6 deg in width and 20.5 deg in height. The neutral (grey) uniform background of the screen had a luminance of 10.9 cd m$^{-2}$. Observers saw two rectangular areas on both sides of the central fixation point. These areas were 9.19 deg in width and 6.72 deg in height, located symmetrically 2.12 deg from the fixation point in the horizontal direction. Both areas were filled with a sinusoidal distribution of luminance which varied in the horizontal direction. The spatial frequency of the vertical grating was 0.65 cycles deg$^{-1}$. As soon as the gratings appeared, they started to move at different velocities, ie one faster than the other. There were three possible combinations of velocities: 0 deg s$^{-1}$ versus 1.53 deg s$^{-1}$ (zero – slow), 0 deg s$^{-1}$ versus 6.12 deg s$^{-1}$ (zero – fast), and 1.53 deg s$^{-1}$ versus 6.12 deg s$^{-1}$ (slow – fast). The range of used velocities was restricted owing to the periodic nature of the gratings—at some spatial ‘jumps’ between frames the impression of forward motion disappears or reverses. At the beginning of each trial, the grating was red or green with the maximal

![Figure 3. Mean answer times for correct responses as a function of velocity. Vertical bars denote 95% confidence limits.](image-url)
luminance equal to 25.6 cd m\(^{-2}\) (red) or 25.4 cd m\(^{-2}\) (green) [measured by ColorCAL (Cambridge Research Systems)]. The slight difference in luminosity (0.2 cd m\(^{-2}\)) occurred because of technical reasons, but this cannot account for more than 1 ms in perceived difference (see Allik and Kreegipuu 1998; Kreegipuu and Allik 2004; figure 1). Moreover, as in our previous study (Kreegipuu et al 2006), the effect of velocity on reaction times to achromatic change (luminance) and chromatic change (colour) was similar, the slight difference should not be crucial here. The experimental setup is illustrated in figure 4.

For the red grating, the L-cone contrast was 1.54 and the M-cone contrast was 0.01. For the green grating, the L-cone contrast was 0.88 and the M-cone contrast was 1.18. Between red and green bars, the L-cone contrast was 0.37 and the M-cone contrast was 1.16. The colours were chosen to minimise blue/yellow channel activation.

At random intervals at 600 to 1400 ms from the beginning of the trial, both gratings changed in colour either from green to red or red to green. There was an SOA between these two changes that varied in 7 steps from \(120\) ms (faster-moving grating changed in colour first) to \(-120\) ms (slower-moving grating changed in colour first).

3.1.3 Procedure. The observers were asked to judge which of the two gratings appeared to change in colour first. They were asked to give responses by pressing either button (“left first” or “right first”) on the response box. The answer time was measured from the moment of first colour change to the press of the button.

3.2 Results
Responses were coded in terms of the probability of the “colour change of the faster-moving grating occurring first” response (the proportion of reports where the colour change in the faster-moving grating was perceived before the colour change in the slower-moving grating). A cumulative Gaussian psychometric function was approximated to the empirical data points by a nonlinear estimation procedure to establish the least-square deviation between them; the fit was calculated for each condition and velocity and for each combination of velocities (zero – slow, \(r^2 = 0.98\); zero – fast,
Figure 5 presents the average psychometric functions for all three combinations of velocities. Once again, the individual psychometric functions did not converge on the same PSE value, varying over conditions from −90 ms (faster must be delayed to be perceived as simultaneous with slower one) to +90 ms (slower must be delayed to be perceived as simultaneous with faster one), for combinations zero−slow from −41 ms to +35 ms, for zero−fast from −90 ms to +90 ms, and for slow−fast from −46 ms to +70 ms. A repeated-measures ANOVA revealed no significant effect for combinations of velocity ($F_{2,8} = 0.42$, $p = 0.67$), indicating that when comparing colour changes in two moving gratings, the faster-moving one is not perceived significantly earlier than the slower-moving or stationary one. There was considerable variability in PSEs among individual observers ($F_{4,14} = 7.13$, $p = 0.002$) and a significant interaction between the observer and the combination of velocities ($F_{8,64} = 5.01$, $p = 0.0001$). These results show that PSEs do not regularly change as a function of velocity. Indeed, in the aggregated data, the PSEs show the opposite tendency of what would have been expected (see figure 5): it takes longer to perceive a colour change in a faster than in a slower-moving stimulus. As in experiment 1, we also measured the time observers needed to make their decisions. The answer times were not affected by the velocity of the moving gratings ($F_{2,8} = 0.223$, $p = 0.805$), being within ±7 ms of the mean value of 530 ms. The interaction between the observers and the combination of velocities was not significant ($F_{8,69} = 0.37$, $p = 0.798$).

**4 Experiment 3**

In this experiment we measured reaction time to colour change in a moving grating to see whether this is perceived similarly to colour change in a single moving bar. Three different spatial frequencies were used to investigate whether the results would be similar to our previous findings with a single moving bar when lower spatial frequencies are used.
4.1 Method

4.1.1 Participants. Three female observers (aged 24–33 years) participated in this experiment. All participants had normal or corrected-to-normal vision and reported no deficit in colour vision.

4.1.2 Apparatus and stimuli. The apparatus was the same as that used in experiment 2. The three spatial frequencies were 0.65, 0.23, and 0.07 cycles deg\(^{-1}\). Except for the lowest spatial frequency (when the window in which the grating was shown was horizontally expanded over the screen so that the grating would appear to be moving as opposed to flickering), a rectangular window filled with a sinusoidal grating (of the same size as in experiment 2) appeared on the right or the left side of the fixation point.

4.1.3 Procedure. In all conditions, a monochromatic sinusoidal grating moving with a constant velocity (0, 1.53, 3.06, 6.12, or 9.2 deg s\(^{-1}\)) changed in colour from green to red or vice versa at a random moment in time between 500 and 1200 ms from the beginning of motion. Each observer performed 810 trials: 270 trials in each task, and 54 trials at each velocity. The observer’s task was to press the button on the response box as soon as she noticed the change in colour.

4.2 Results

Only RTs below 1000 ms (RTs over 1000 ms were considered as misses) and over 100 ms (RTs below 100 ms were considered an anticipatory responses) were included in the analysis (2370 responses from all 2430 trials). A factorial ANOVA showed a statistically significant effect for velocity ($F_{4,8} = 9.21$, $p = 0.004$). As can be seen in figure 6, RTs showed a slight tendency to increase with velocity, indicating that it takes more time to detect colour change in faster-moving gratings. The interactions between observers and velocity ($F_{8,16} = 0.516$, $p = 0.828$) and between velocity and spatial frequency ($F_{8,16} = 1.88$, $p = 0.134$) were not significant. There was a significant interaction between observers and spatial frequencies ($F_{4,16} = 8.55$, $p = 0.0007$).

Thus, contrary to what was found with single moving objects, the velocity of the gratings slightly increases the time needed to detect a change in colouration.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Mean reaction times (RTs) (with 95\% confidence limits) for different series of spatial frequency as a function of velocity.}
\end{figure}
General discussion

Our experiments demonstrated two points of considerable interest. First, there was a clear disparity between RT (reacting to an event) and TOJ (comparing temporal order of two events) tasks in determining the moment when a moving object appears to change in colour. While the RT task demonstrated a substantial reduction in detection time with an increase in velocity when a single moving object changed in colour (Kreegipuu et al 2006), there was no corresponding shortening of the delay when the TOJ task was used (experiment 1). This disparity demonstrates, once again, that it is very difficult to maintain the view that there is some invariable perceptual latency for the whole visual system (Allik and Kreegipuu 1998). Measured by one particular method, for example RT, there may be a considerable perceptual delay, but other perceptual tasks (such as TOJ) may reveal no, or a significantly reduced, delay. Researchers have repeatedly found that RT and TOJ estimates of perceptual lag are slightly different (Cardoso-Leite et al 2007; Roufs 1963, 1974). When perceptual lag is measured in dependence of stimulus intensity, RT estimates increase more rapidly with a decrease in intensity compared to other procedures such as intermodal or intra-modal temporal-order judgments (Roufs 1974). The present study demonstrates even greater disparities: the RT reveals a decrease in detection time as velocity increases, while in the TOJ procedure velocity had no influence. This dissociation indicates that the internal representation on the basis of which the observer makes the decision about simultaneity of the two perceptual events and the time required to build this internal representation are not necessarily related.

One possible explanation is that RT and TOJ are based on two different perceptual representations and that two different decision criteria, one for perception (TOJ) and the other for action (RT), are applied to the same representation (Cardoso-Leite et al 2007; Sternberg and Knoll 1973). It is logical to expect that in the RT experiment the response would be delivered as soon as the internal representation of the relevant event has reached the conscious threshold. For some reason colour change in a fast-moving object reaches consciousness earlier than information about exactly the same change in a slow-moving or stationary object. However, when the observer is instructed to make a decision about the relative order of two perceptual events, she/he may rely on some other information, not necessarily the moments when the events become available in consciousness for the first time. The comparison process of the internal representations of the two judged events may not have access to temporal information precise enough to estimate the exact time when something enters our subjective awareness. It may be that temporal order is judged on the basis of some other information, for example when the representations of the two events have reached maximal distinctiveness (Sternberg and Knoll 1973). If this is so, then it is still paradoxical that a decision which is based on the peak value of the internal response takes the time needed for the internal response to exceed a fixed threshold.

One cannot also exclude the possibility that there is a general tendency to group events that have happened in close succession into one simultaneous perception. Other researchers have also observed that auditory and visual signals of an event that reach an observer at the same point in time tend to become perceptually bound, even when the sources of those signals could not have occurred together (Arnold et al 2005). In other words, unlike RT, temporal order judgments do not reflect differential neural delays for different sensory attributes. Similar conclusions were reached by Nishida and Johnston (2002) who proposed that the perception of the relative time of events is based on the relationship of representations of a temporal pattern they called time markers. They concluded that the perceptual asynchrony effects emerging from the colour-changing stimulus paradigm do not reflect differential neural delays for different attributes; rather, they arise from a faulty correspondence between colour transitions.
and position transitions (motion), which in turn results from a difficulty in detecting turning points (direction reversals) and a preference for matching markers of the same type. Whatever the specific explanation is, the results seriously question the logic of the colour-changing stimulus paradigm (Moutoussis and Zeki 1997a, 1997b; Zeki et al 1991) which assumes that psychometrically estimated values correspond directly to perceptual latencies in the visual system (cf Allik and Kreegipuu 1998; Kreegipuu and Allik 2004; Werner 2007).

Second, the results in terms of answer times were unexpected: when there was a single moving object (experiment 1), the time needed to make a TOJ decreased with an increase in the velocity, but this relationship disappeared when a single object was replaced with a moving grating seen through a stationary window. It seems that a small variation in stimulus configuration (single bar versus gratings) brought about a considerable change in the outcome. Thus, the velocity dependence shown in our previous study (Kreegipuu et al 2006) appears to be attributable to certain stimulus properties, such as the constantly changing spatial position of a single moving stimulus, and, furthermore, seems to disappear when this information is not presented, as was the case with the moving sinusoidal gratings. This discrepancy seems to indicate that the motion of single objects and that of spatially extended textures is analysed by a different set of mechanisms, one of which shows speed-dependence and another which does not. Researchers seem to agree that there are several different stimulus properties, and a corresponding number of perceptual mechanisms, that are responsible for the perception of motion (Lu and Sperling 1995, 2001; Lu et al 1999; Seiffert and Cavanagh 1999; Smith 1994; Smith et al 1998). For example, Lu and Sperling (1995, 2001) have proposed that human visual motion perception depends on three separate motion systems: a first-order system that responds to moving luminance patterns, a second-order system that responds to moving modulations of feature types—stimuli in which the expected luminance is the same everywhere but an area of higher contrast or of flicker is moving, and a third-order system that tracks features in a neural representation of visual space in which the locations of important visual features (‘figure’) are marked and ‘ground’ is unmarked. While moving textures are primarily analysed by lower-order systems relying on motion energy, single objects translating from one location to another are analysed by a higher-order motion-tracking system which, unlike the lower-order systems, is able to integrate information along a movement trajectory. It is known that in dense cinematograms only the shortest displacements are counted (Allik and Dzhafarov 1984; Verghese et al 1999), whereas in less-crowded patterns motion signals can be combined along the trajectory of the moving object (cf Festa and Welch 1997; Krekelberg and Lappe 1999; Verghese et al 2000; Welch et al 1997). Because a faster-moving stimulus activates a larger number of coding units along the trajectory, it can be expected that the detection of colour or contrast changes is facilitated when a larger number of coding units is involved. These coding units, however, must be sensitive to colour because they are able to notice when it changes.

Of course, the number of coding units may not be the whole story. The fact that both the enhancement of colour constancy (Werner 2007) and the detection of change in colouration are specific for object motion patterns goes against an explanation based on low-level motion units. If this were the case, we would have expected an unspecific enhancement of colour constancy in all types of motion pattern (cf Werner 2007). Instead, the phenomenon clearly is object-specific.

Finally, the distinction between TOJ and the time required to make TOJ is also worthy of mention. While TOJ showed no relation to velocity, the time observers spent giving answers about the temporal order of the two events decreased with the increase in velocity of the moving object. It is important to remember that we did not give
any particular instructions about how slowly or quickly to answer. There was certainly no pressure to answer as quickly as possible. Nevertheless, answer times reflected quite accurately the velocity of the moving object, decreasing as the velocity of the object increased. We are not aware of many studies where perceptual decisions and the time needed to make these decisions reflect different stimulus information. In general, there is no necessary relationship between the decisions and the time taken to make these decisions. For example, it takes no more time to produce the final result in a voltmeter as the input voltage increases. Therefore it is even more revealing that such a dissociation exists between the perception of temporal order of events and the time required to give an answer.

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