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DETECTION OF COLOUR CHANGES IN A MOVING OBJECT

Master's thesis

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Tartu 2007

Abstract

The time needed to detect changes in colouration of a single moving stimulus becomes shorter with its velocity (Kreegipuu, Murd, & Allik, 2006). In this study we examined ability to detect colour changes in moving chromatic bars and gratings using two tasks: temporal order judgement and reaction time tasks. In addition visual evoked potentials elicited by the change of colour were registered. The results demonstrated that unlike reaction time to the colour-change of the single moving object both temporal order judgement and detection of changes in colouration of a moving grating were insensitive to stimulus velocity. Possible explanations for this discrepancy are discussed.

Keywords: Motion, velocity, colour-change paradigm, reaction time, temporal order judgement, visual evoked potentials

Running head: Detection of colour-change

Kokkuvõte

Liikuva objekti värvimuutuse tajumine

Aeg, mis kulub üksiku liikuva objekti värvimuutuse tajumiseks lüheneb seoses objekti kiirusega (Kreegipuu, Murd, Allik, 2006). Käesolevas töös uurisime värvimuutuse avastamise võimet liikuvatele kromaatilistele üksikstiimulitele ja võredele, kasutades selleks kahte erinevat ülesannet - ajalise järgnevuse hindamine ning reaktsiooniaja mõõtmine. Lisaks registreeriti ka visuaalselt tingitud potentsiaale (*visual evoked potentials*, *VEPs*) värvimuutuse sündmusele. Tulemused näitavad, et erinevalt üksikobjekti värvimuutuse tajumisest, ei avalda liikumiskiirus ajalise järgnevuse hinnangutele ega ka liikuva võre värvimuutusele mõju. Käsitletakse nimetatud lahknevuse võimalikke seletusi.

Võtmesõnad: Liikumine, kiirus, värvimuutuse paradigma, reaktsiooniaeg, ajalise järgnevuse hindamine, visuaalselt tingitud potentsiaalid

Läbiv pealkiri: Värvimuutuse avastamine

INTRODUCTION

Semir Zeki with colleagues introduced an elegant colour-changing stimulus paradigm in order to determine the relative speed of processing different stimulus attributes (Moutoussis & Zeki, 1997a,b). When moving objects are repeatedly changing colour (between red and green, for example) and alternating their motion direction (upward and downward) with the same frequency, then colour change must occur approximately 80 ms after changes in direction to be perceived as synchronous. They proposed that this asynchrony is due to the fact that the colour and motion analysing systems occupy anatomically distinct locations in the visual cortex and these two systems have different perceptual latencies: we become conscious of colour before we become conscious of motion (Zeki, Watson, Lueck, Friston, Kennard & Frackowiak, 1991). This spectacular demonstration has served as a crucial evidence for a generalization that there are many consciousnesses distributed in time instead of a single unitary consciousness (Zeki, 2003).

The colour-changing stimulus paradigm is based on a hidden assumption that velocity does not affect the detection of the colour-change. It is assumed that the colour-change of a moving object is detected identically irrespective of the velocity of the moving target. Trying to reveal ideas behind the silent assumption, it seems that the proponents of this paradigm assume the existence of two types of colour detectors (coding red and green respectively) which switch on as soon as one of them has detected the presence of the colour they are turned to. It does not matter whether this colour belongs to a moving or stationary object – colour-coding units are movement-blind and they just measure presence of radiation with a particular wavelength. However, in a recent study it was shown that the detection of changes in colour depends on the velocity of moving targets that seriously undermine the whole logic of chronometrization of the perceptual delay by the colour-changing stimulus paradigm. The time that was needed to detect changes in colouration becomes shorter with velocity (Kreegipuu, Murd & Allik, 2006).

It is counterintuitive, to some extent, that it takes less time to detect when a green moving object turns instantly red while it moves fast rather than slow. Therefore it is essential to demonstrate that it is indeed velocity that affects detection of colour-change and nothing else, for example readiness to deliver the response. When a single object moves across the monitor screen the observer has certain expectation when and where the colour change could happen. In the beginning of the movement trajectory the probability of colour-change is smaller than in its final part, provided that the colour-change has not happened until this moment. It is well known that the reaction time (RT) increases with stimulus uncertainty (Mattes, Ulrich, & Miller, 2002; Näätänen, 1972). Indeed, our previous results demonstrated that RTs decrease with the increase of colour-change probability. However, this decrease was independent of the effect of velocity: it was still easier to detect colour-change in a fast moving stimulus than in a slow moving or stationary stimulus (Kreegipuu et al., 2006; see also Monnier & Shevell, 2004).

Although the fact that the time needed to detect changes in colouration becomes shorter with velocity was rather firmly established, it would be not only interesting but also important to create an experimental situation in which probability of colour-change is not related to the readiness to deliver the response. There are two different ways how to decouple the stimulus spatial and/or temporal uncertainty from the response readiness. One obvious way is to use responses in which readiness is not relevant. For example, the observer can be instructed to compare the colour-change of a moving object with some other event, for example a short acoustical signal, which could serve as a reference point. Provided that the reference signal is processed invariantly, it should be expected that a colour-change of a fast moving object is perceived earlier in the relation to the reference signal than the similar change of a slow moving or even stationary object.

Another possibility to eliminate spatial and/or temporal uncertainty is to use movement inside a spatially confined area instead of a single object which travels across the screen changing its spatial position. Let suppose that the luminance distribution is modulated inside the confined area and this distribution moves with a constant velocity within this area. In this case there are no spatial cues signaling approach to the final spatial position where colour-change could ultimately happen if it has not happened before.

In order to decouple the stimulus spatial and/or temporal uncertainty from the response readiness four experiments were carried out.

In Experiment 1, an auditory stimulus was presented as a reference signal with which the colour-change of a moving object was compared. The observer's task was to decide whether a short acoustical signal was delivered before or after the change in colour of a moving object, translating with different velocities across the screen, had happened.

In Experiment 2, the observer's task was to compare two colour-changes and decide which of them happened first. Two rectangular areas were filled with sinusoidally modulated luminance forming two monochromatic vertical gratings with the identical spatial frequency.

These two gratings moved with two different velocities and changed their colour at two independent moment of time: the green grating turned instantly to red or the red grating turned instantly to green. On the basis of our previous results we expected that the colour-change of a faster moving grating appears earlier in time than the colour-change of the slower moving grating even if the both changes have happened at the same moment of time.

In Experiment 3, we measured the time that was required to detect change in colour of a monochromatic grating moving with different velocities. Assuming that the colour-change of the grating is perceived similarly as the colour-change of a single object translating across the plane one could expect that the time required to notice change in colouration becomes shorter as velocity increases.

Finally, in Experiment 4, we measured visual evoked potentials (VEP) to the colour-change of a moving grating. We assumed that if velocity of gratings facilitates detection of their change in colouration then this facilitation might be reflected in the amplitude and latency of cortical potential evoked by this change.

EXPERIMENT 1

In temporal order judgments (TOJ) studies where auditory stimulus has been compared with visual stimulus, the auditory stimulus has to be delayed to be perceived simultaneously with the visual one (Alais, & Burr, 2003; Arrighi, Alais, & Burr, 2005; Hine, White, & Chappell, 2003). Here, however, our purpose was to examine whether the colour-change of a faster moving stimulus is detected earlier than the colour-change in a slower moving stimulus in different experimental condition, so we used an auditory stimulus as a reference signal with which the colour-change of a moving visual object was compared. When keeping an auditory signal constant during the trials, the time to perceive this signal should remain invariable, and, according to our previous study it could be expected that we see the difference in the time needed for noticing the colour-change in a faster *vs* slower moving stimuli.

Two experimental conditions were used – in fixating-condition observers were instructed to fixate a little cross in the middle of the screen during the trial, and in the tracking-condition to track the moving (or stationary) object. The reason for this is the matter that when fixating one point in the visual field, the moving object is constantly changing its position on retina, but tracking it enables to keep the retinal position almost unchangeable. Both conditions induce impression of motion, so it is important to examine, whether the time needed to detect the colour-changes, depends on the retinal velocity or the physical velocity of the object. If the shortening of time needed to detect colour-change is caused by retinal velocity, there should not appear any effect of velocity, since the retinal velocity in tracking-condition is near to zero.

Method

Experimental setup was very similar to our previous experiments (Kreegipuu et al., 2006), except the instruction and addition of auditory stimulus.

Participants. Five female observers (aged 22-24), three well-trained observers and two naïve ones, took part in the experiment. They all had normal or corrected-to-normal vision and had no hearing abnormalities.

Apparatus and stimuli. Stimuli were generated on the HP 19” monitor screen (approximately 22.08º x 17º) with the help of a Cambridge Research Systems VSG 2/3. In order to achieve a better temporal resolution (200Hz frame rate) the spatial resolution was reduced to 186 vertical lines and 752 horizontal positions. Time needed to make TOJ was measured using external clock of VSG 2/3 card providing the precision of at least 1 ms. The background luminance was 1.92cd/m^2. The colour stimuli were red or green rectangular bars (1.96º x 0.25º) with approximately equal luminance of 12.7cd/m^2. These two values around the luminance of the colour bar were chosen to obtain approximately comparable perceptual salience of the change. Observers sat at a 90cm viewing distance from the screen and were instructed to fixate a small cross in the centre of the screen or to track the moving (or stationary) stimulus. The auditory stimulus was a 1000Hz monotone beep that was presented for 0.1s. The auditory stimulus was presented through the speaker. The order of sessions (tracking or fixating-condition) was randomized.

Procedure. Each trial started with the appearance of either stationary or moving rectangular bar. The bar appeared at the right or left edge of the screen and started immediately to move horizontally across the screen, with one of two velocities 5.9 or 17.6º/s. The bar changed its colour (from red to green or vice versa) at one of ten possible positions in the central third of the screen. The stationary stimulus was presented at one of the ten possible positions, where the colour-change took place. The stimulus-onset asynchrony (SOA) between the colour-change and auditory signal stimuli varied between -225 (acoustical signal before the colour-change) and +225ms. Observers were instructed to judge which of the two stimulus, auditory signal and colour-change of a moving bar, appeared first. There were two different types of series. In one of them the observer was instructed to fixate the central fixation mark (fixation condition). In the other type of series the observer was allowed to follow moving stimulus with her eyes (tracking condition). Each observer performed 420 trials per condition and velocity (2,520 trials per person).

Results and Discussion

The responses were coded in terms of the "colour-change occurred first" probability that is percentage of reports that the change in colour happened before the acoustical signal. Data points in the empirical psychometric function were approximated by a cumulative Gaussian function using a nonlinear estimation procedure. The horizontal position of the psychometric function was measured by the location of 0.5 point. At that SOA value the point of subjective equality (PSE) was reached since the both response alternatives were chosen with equal probability. The goodness of fit was estimated by comparing the mean approximation error (the mean deviation of a data point from the best fitting psychometric function) with the mean standard error of data points. In general, the approximation was satisfactory because the approximation error was not larger than the mean standard error. Figure 1 show mean PSE values for five observers in two observation conditions (fixation and tracking) and three different velocities (0, 5.9, and 17.6 °/s).

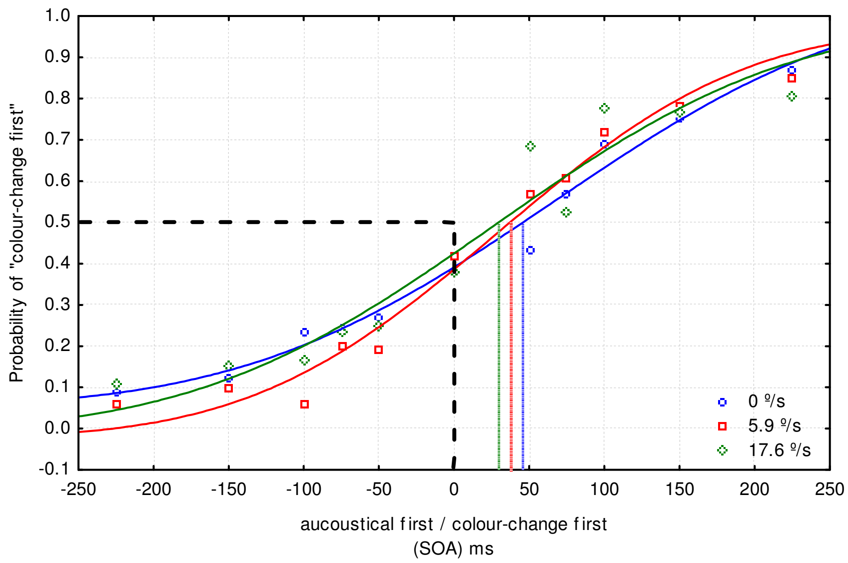

Figure 1. *PSE values for all observers. Presented values show how much earlier one of two signals should be presented to be perceived as simultaneous to another. Positive values mean that the colour-change should be presented first to be perceived simultaneously with the colour-change. Broken line indicates perfect perceptual simultaneity.*

Although, after visual inspection of the figure: PSEs are ordered to indicate less processing time for the colour-change of faster moving bar, we do not consider it reliable enough. When varying the onset asynchrony between the colour-change and acoustical signal, *repeated measures* ANOVA for the temporal order judgements revealed considerable individual differences between observers [F(4,12592)=3.51, p=.007], significant effect of task condition [F(1,12592)=10.35, p=.0013], but insignificant effect of velocity [F(2,12592)= 0.39, p=.678] and insignificant interaction between velocity and condition [F(2,10235)=.08, p=.923], suggesting that the possible facilitating effect of velocity of colour-changing moving object assumed, does not reveal in temporal order judgements.

There was a significant interaction between an observer and velocity [F(4,12585)=3.19, p= .013], and insignificant interaction between velocity and condition [F(2,12595)=0.19, p=.33], which refers that the temporal order judgments varied inconsistently as a function of velocity in both conditions. The individual point of the subjective equality (PSE) varied between -87ms (visual stimulus must delay) and +163ms (acoustical signal must delay). There appeared no consistency or stability in PSE between or within the observers, condition or velocity that does not allow us to trust the obvious order of PSE-s in Figure 1.

Although, the aim of this experiment was not to examine the subjective temporal order between acoustical and visual signal, but to see whether the colour-change of a faster moving stimulus is detected earlier than the colour-change in a slower moving stimulus, the results of individual PSEs are consistent with the previous study conducted by Stone *et al.* (Stone, Hunkin, Porrill, Wood, Keeler, Beanland, Port, & Porter, 2001), where PSE varied between -21ms (sound 21ms before light) and +150ms. They also varied the viewing distance and stimuli and concluded that the PSE to be distance invariant. However, when changing the instruction from fixating to tracking the stimuli or the series of velocity, there were significant differences in our experiment. Here, the effect of the velocity on PSE seems to be highly individual and task-dependent.

Par with his co-authors (Par, Kohlrausch, & Juola, 2002) have assumed that differences in PSE might be the consequence of different response strategy. Since the observers did not have an option to respond “simultaneous” - although there were cases of simultaneity presented - , and they had to decide “which came first”, - they might have used a strategy of responding, when they actually perceived the stimuli to be simultaneous. For example, when an observer could not decide or was not sure which modality came first, some of them always (or in most of cases) responded “colour-change first”, others “acoustic signal first”. At the same time, individual PSE-s show that the strategies observers used were not very consistent, perhaps due to unnatural or difficult task.

Kanabus *et al.* (Kanabus, Szelag, Rojek, & Pöppel, 2002) have considered of two different kinds of response strategies in the auditory modality from which only one is comparable to the response strategy in the visual modality. So, when the observers adopt different strategies, one having a strategy comparable to the one used in case of visual stimulus, the individual differences are likely to appear. Yet, this might explain the individual differences in subjective equality point, but there is no reason to presume that the observers used different strategies in different velocities that were presented randomly.

We also measured the time that observers spent to give their answers. Although our observers were not given any specific instructions how fast or slow they need to be giving their answers, they demonstrated a clear dependence on velocity, very much like experiments in which the colour-change was detected (Kreegipuu et al., 2006). Figure 2 demonstrates that the decision time of the correct choices (the reported temporal order corresponded to actual order of events) reduces with the increase of velocity.

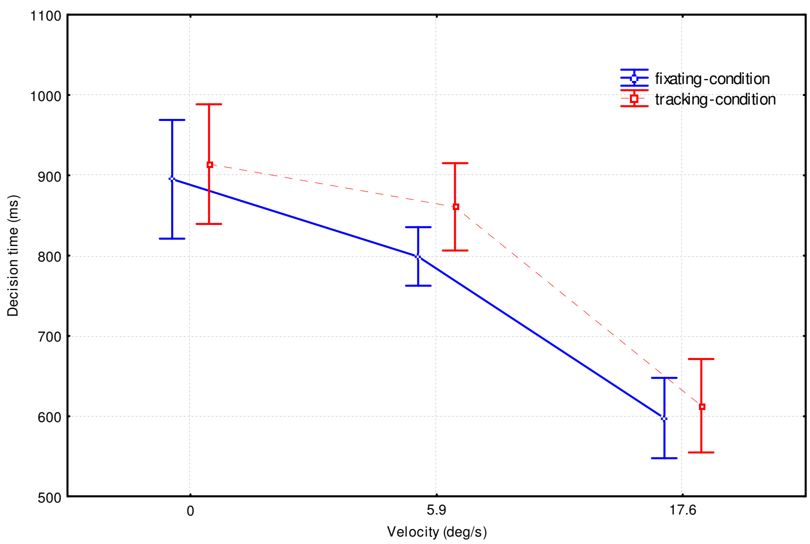

Figure 2. *The mean decision times to correct responses as a function of velocity. Vertical bars denote 95% confidence limits.*

In both conditions (fixating and tracking) *factorial* ANOVA revealed significant effect of velocity [$F(2,1794)=52,733$, $p=.0000$]. The effect of condition to time spent to give answers was insignificant [$F(1,12570)=.9662$, $p=.756$], also the interaction observer x velocity x condition was insignificant [$F(8,10205)=1.434$, $p=.177$]. Although, as can be seen from the

Figure 2, the time for change detection in fixating-condition are somewhat shorter, the interaction between condition and velocity was insignificant [$F(2,1794)=0,363$, $p=.695$]. This shows that the time required to make TOJ was sensitive to the velocity of a moving object: with the increase of velocity less time was needed to make a decision. Surprisingly, we found that the interaction between the type of answer (“acoustical signal first” or “colour-change first”) and velocity was insignificant [$F(2,1788)=1.72$, $p=.18$], referring that time spent on making decision “acoustical signal first” was also facilitated with the velocity of moving object changing colour.

This experiment provide an example of divergence between subjective appearance (TOJ) and objective performance (time required for TOJ) from which only the latter revealed the influence of velocity on the detection of change in colour. This divergence may mean that an internal representation on the basis of which the observer is making her decision about simultaneity of two perceptual events and time required to build this internal representation are not necessarily related. In particular this may mean that simultaneity in the TOJ task is not decided on the basis of the moments when these two perceptual events enter the consciousness. Also similar velocity-relatedness for “acoustical first” and “colour-change first” speaks for a common perceptual representation for the events in case of TOJ-task.

In temporal-order task the effect of velocity on the detection seems to be highly individual. Contrary to that, the response or decision times demonstrate the tendency found in reaction time experiments.

EXPERIMENT 2

There is a problem with moving stimuli, namely people fail to ignore the temporal and spatial uncertainty induced by information of the constantly changing position of a moving stimulus. In this experiment we are eliminating or at least reducing the spatial uncertainty using two areas (that do not change their position in space) filled with the sinusoidal distribution of luminance which varied in the horizontal direction.

Method

Participants. Five observers (1 male and 4 females, aged 24-33) three well-trained and two naïve observers took part in this experiment. They all had a normal or corrected-to-normal vision.

Apparatus and stimuli. Stimuli were presented on the monitor screen Mitsubishi Diamond Pro 2070SB (frame rate 140Hz) which from the viewing distance of 90 cm subtended 27.6 ° in width and 20.5° in height. The neutral (gray) uniform background of the screen had luminance 10.9cd/m^2. The observer saw two rectangular areas on the both side from the central fixation point. These areas were 9.19° in width and 6.72° in height locating symmetrically 2.12° from the fixation point in the horizontal direction. The both areas were filled with the sinusoidal distribution of luminance which varied in the horizontal direction. The spatial frequency of the vertical grating was 0.65 cycles per degree. As soon as gratings appeared on the screen they started to move one with faster velocity than another. There were three possible combinations of velocities: 0°/s vs. 1.53°/s (zero-slow), 0°/s vs. 6.12°/s (zero-fast), and 1.53°/s vs. 6.12°/s (slow-fast) stimuli. In the beginning of each trial the grating was red or green with the maximal luminance equal to 24.2cd/m^2 (red) and 24.5cd/m^2 (green). In a random interval from 600 to 1400 ms from the beginning of trial the both gratings instantly changed their colour either from green to red or red to green. There was a stimulus-onset asynchrony between two changes which varied between -120 (faster moving grating changed its colour first) and +120 ms (slower moving grating changed its colour first).

Procedure. The observers were asked to judge which of the two stimuli appeared to change its colour first. The responses were coded in the term of probability that the faster of two moving gratings was indicated to change its colour first.

Results and Discussion

Data was analysed with *repeated measures* of ANOVA, observer was set as random factor. The analysis of answers showed insignificant effect of combinations of velocity [$F(2,2145)=1,98$, $p=.249$]. Figure 3 presents mean of the points of subjective equality for all three possible conditions. The individual PSEs show no consistent tendency, varying between -70ms (slower first) and +90ms (faster first).

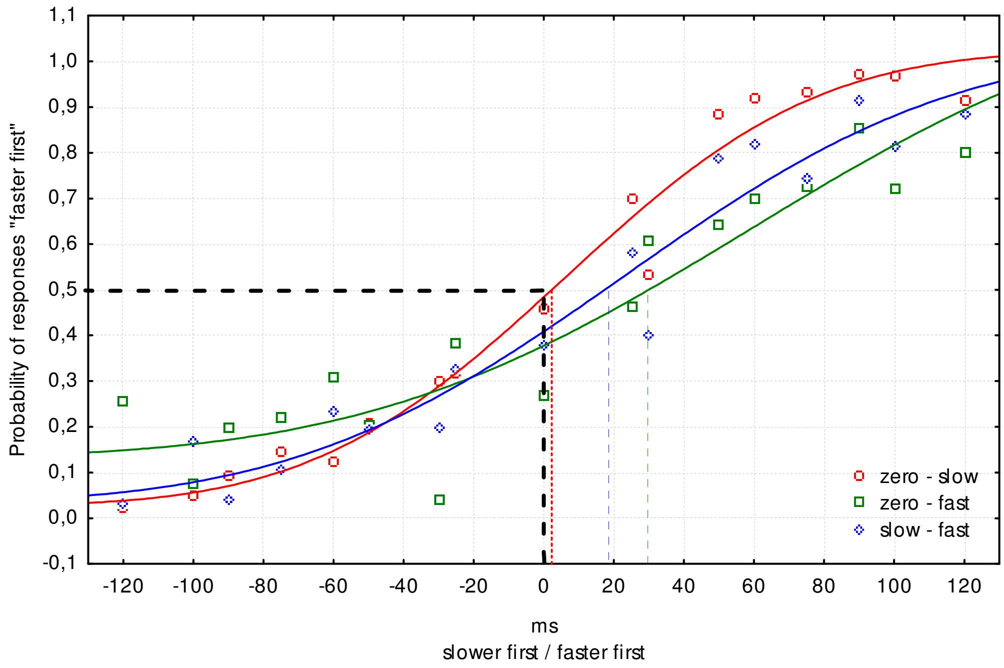

Figure 3. *Probability of responses „faster first“ for different combinations of velocities. Positive values show that the faster moving grating was changing colour first and negative values for slower grating changing colour first.*

Taken account the significance of individual differences a significant effect of the observer [F(8,2025)=6.059, p=.00000] and a significant interaction between the observer and combination of velocities (F(8,2145)=4.69, p=.00006], the results show that PSEs are not changing regularly as a function of velocity. In aggregated data, the PSEs show even opposite tendency depending on velocity (Figure 3): it takes longer time to perceive the colour-change of faster moving stimulus.

As in Experiment 1, we also measured the time observers spent on giving answers. In a figure 4 it can be seen that unlike in Experiment 1, with single moving stimulus and auditory stimulus, the response times were not effected by the velocity of moving gratings [F(2,2145)=.007, p=.801]. The interaction between an observer and combination of velocities was insignificant [F(8,2145)=.408, p=.797].

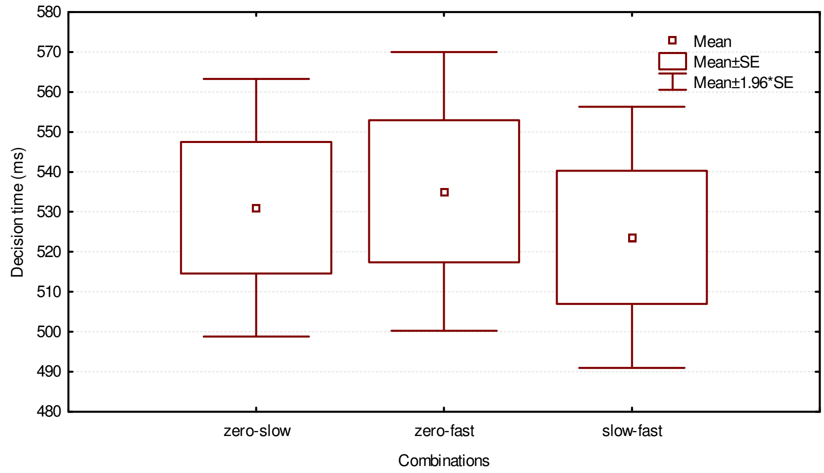

Figure 4. *Decision times (ms) of correct responses (both "slower first" and "faster first") in all three conditions.*

EXPERIMENT 3

In this experiment we used one rectangular grating moving with different velocities to measure RTs to a colour-change. Assuming the colour-change of grating is perceived similarly to a single moving object we used in our previous study (Kreegipuu et al., 2006), it could be expected that the time for noticing colour-change becomes shorter as velocity increases.

Method

Participants. Five observers (1 male and 4 females, aged 24), two well-trained and three naïve ones participated in this experiment. All participants had normal or corrected-to-normal vision.

Apparatus and stimuli. Apparatus and stimuli were identical to the ones used in Experiment 2. In this experiment only one sinusoidal grating was used and five possible velocities were used.

Procedure. Two rectangular areas filled with the sinusoidal gratings appeared at 2.12º on the right or left side from the fixation point, the sinusoidal grating changed colour from green to red or vice versa, moving with one of five velocities: 0, 1.53, 3.06, 6.13 or 9.2º/s. The onset of colour-change was chosen in a random interval from 500 to 1200 ms from the beginning of trial. Each observer performed 540 trials (108 per velocity).

Results and Discussion

Only RTs below 1000ms and over 100ms were included to analysis. Data was analysed using *factorial* ANOVA with observer as a random factor. Figure 5 presents the mean RT to the colour-change as a function of gratings velocity, since the interaction between an observer and velocity was insignificant [F(16,2583=1,162, p=.292].

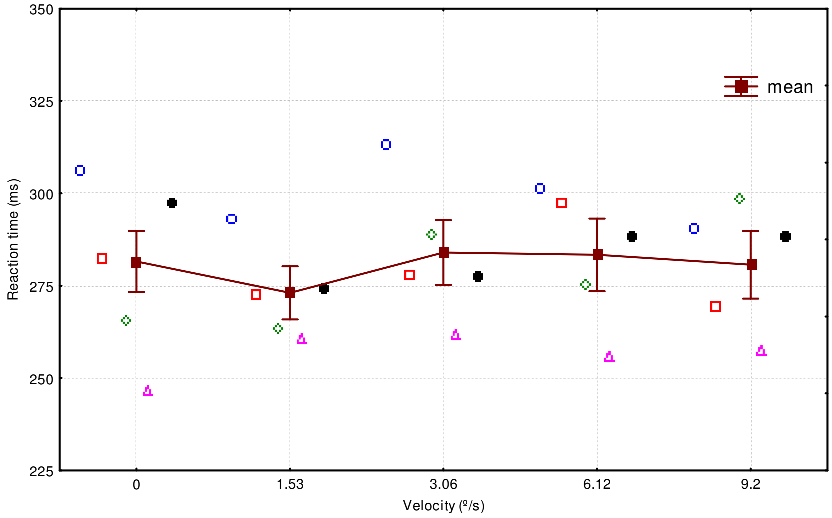

Figure 5. *The mean reaction times (with 95% confidence limits) to changes in colour of gratings moving with different velocities. The single plots present individual mean RTs for different velocities.*

Unlike a single moving object in previous study (Kreegipuu et al. 2006) velocity of the moving grating had no effect on time required to detect changes in colouration of a moving grating [F(4.3105)=.95, p=.43].

EXPERIMENT 4

To reduce the effect of temporal summation of the intensity, which may take place, when the intensities on the retina are changing too rapidly, we next varied the spatial frequency of sinusoidal grating, (that also helps to reduce the effect of practicing) to measure reaction times (RT). We also measured visual evoked potentials to the colour-change, assuming that if the velocity of gratings facilitates the detection of colour-change, it should reflect in the latency and amplitude of the VEPs.

Method

Participants. Three female observers (age range 24-33) participate in this experiment. All participants had normal or corrected-to-normal vision.

Apparatus and stimuli. The apparatus was identical to the one used in Experiment 2 and 3. The spatial frequency of sinusoidal grating stimulus was varied and in one series (with lowest spatial frequency) the grating was horizontally expanded over the screen.
The electroencephalogram (EEG) parameters (registered with BioSemi's system *Active One*, and *Analyzer* 1.05 from Brain Products, GmbH was used for data analysis): recording at fourty electrodes corresponding to the International 10/20 electrode placement system points(Fz, Fpz, F3, F4, T3, T4, C3, C4, Cz, Pz, , T5, T6, O1, O2 according to 10:20 system, Jasper, 1958), off-line referenced to linked ears Additionally, the Common Mode Sense (CMS) active electrode was placed between Fz and Cz and the Driver Right Leg (DRL) passive electrode on the observer's neck. Vertical and horizontal eye movements were registered with two bipolar electrodes for both. The DC mode and sample rate of 1024 Hz was applied for recording. Data were filtered (0.1 Hz low cutoff and 30 Hz high cutoff filters, both 24 dB/oct) and epoched around the colour-change (-100 to + 1000 ms). Ocular artefact was removed with Gratton and Coles algorithm used by Analyzer that corrects ocular artifacts by subtracting the voltages of the eye channels, multiplied by a channel-dependent correction factor, from respective EEG channels. For a baseline correction a 100 ms interval before the colour-change was selected and segments were tested for several known artifacts (50 μV allowed voltage step per sampling point, maximal allowed difference within the segment 50 μV, maximal absolute amplitude +/- 100 μV and lowest activity criterion of 0.5 μV per 100 ms). Segments were averaged for different velocities and three observers and automatic peak detection was used to find peaks P1, N2 and P3 on the averaged ERP curve.

Procedure. In two conditions sinusoidal grating bar (same size as in Experiment 2 and 3) appeared on the right or left side of the fixation point and in the third condition the grating was expanded to the width of screen, in all conditions the sinusoidal grating changed colour from green to red or vice versa, moving with one of five velocities: 0, 1.53, 3.06, 6.13 or 9.2°/s. Three spatial frequencies used were 0.65 cyc/deg, 0.23cyc/deg and 0.07 cyc/deg. Each observer performed 810 trials, 270 trials per task, 54 trials per each velocity.

Results and Discussion

Reaction time. Only RTs below 1000ms and over 100ms were included to analysis. The *factorial ANOVA* showed statistically significant effect of velocity [$F(4,2325)=2.8004$, $p=.025$]. The interactions between an observer and velocity [$F(8,2325)=.239$, $p=.984$] and between velocity and series of spatial frequency [$F(8,2325)=1.67$, $p=.100$] were insignificant.

There was a significant interaction between observer and series of spatial frequencies [F(2,2325=7.695, p=.0000].

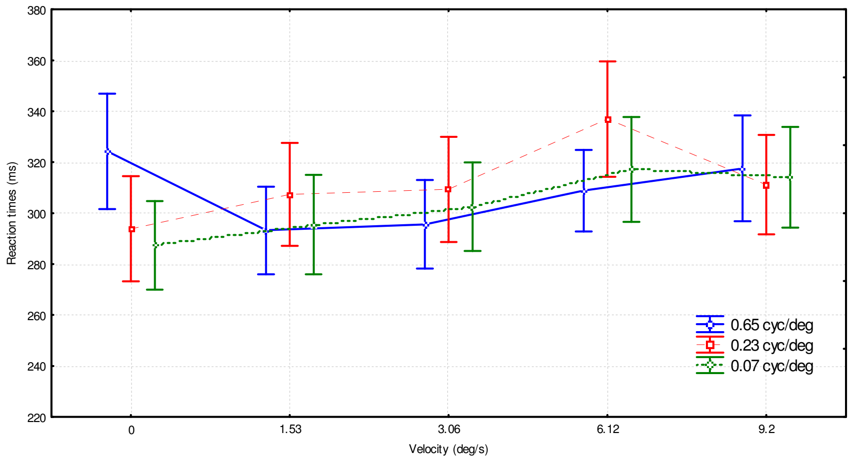

Figure 6. *Mean reaction times (with 95% confidence limits) for different series of spatial frequency as a function of velocity.*

Visual Evoked Potentials. Data from the O1 electrode was included into analysis, since the effects were expectedly most salient in this point. Figure 7 presents the grand-average of P1, N2 and P3 components. Single sample *t*-test revealed that N2 and P3 peaks for O1 were statistically significant from zero in all conditions (for N2 ranging from p= .002 to p=.00005; for P3 from p=.033 to p=.0002), the peak of P1 were statistically significant from zero (p=.0004) only in the condition of lowest spatial frequency. There was no correlation found between RT and peaks other than the correlation between P1 latency and RTs in the condition of lowest spatial frequency (r=.95, p<.05). The *repeated measures* ANOVA reveals significant interaction between velocity and P1 latencies in the condition of lowest spatial frequency (0.07 cyc/deg) [F(4,8)=8.831, p=.005] (see Figure 8). Interactions between P1 latencies and velocity in the condition of spatial frequency (0.23 cyc/deg) and (0.07 cyc/deg) were insignificant [F(4,8)=2.79, p=.101, F(4,8)=2.99, p=.088, respectively].
No significant interaction between the amplitude of P1 and velocity was found [condition 1 F(4,8)=1.36, p=.33; condition 2 F(4,8)=2.75, p=.104; condition 3 F(4,8)=3.144, p=.079].

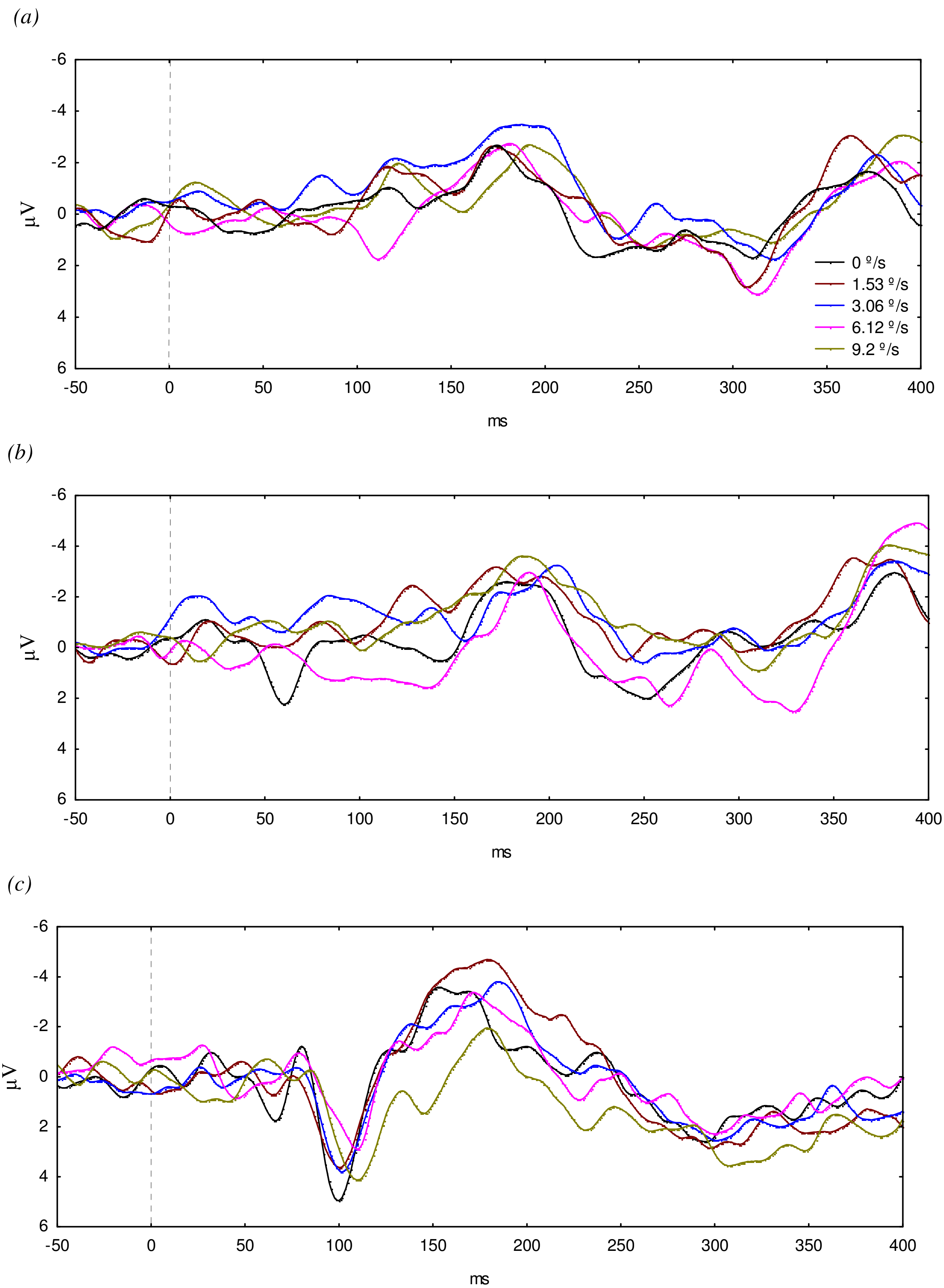

Figure 7. *Grand-average O1 of P1, N2 and P300 through all experimental conditions. (a) condition with highest spatial frequency (0.65 cyc/deg), (b) 0.23 cyc/deg, (c) condition with lowest spatial frequency (0.07 cyc/deg).*

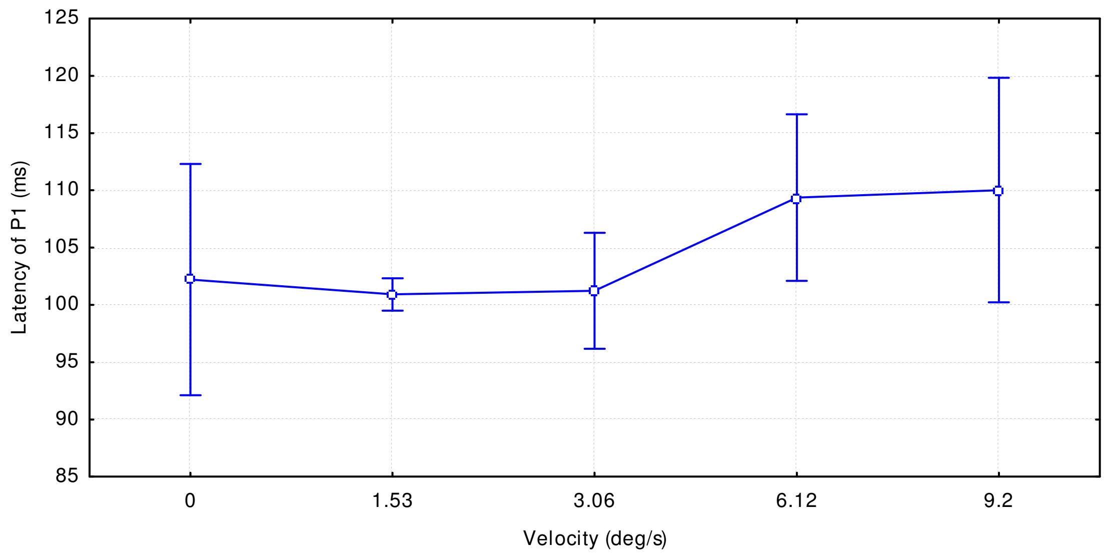

Figure 8. *Latency of P1 as a function of velocity in the condition of lowest spatial frequency (0.07 deg/s).*

P1 has been linked with parvocellular processing, mostly with ventral stream features such as colour and shape and their changes (Kimura, Katayama, & Murahashi, 2006; Armstrong, Neville, Hillyard, Mitchell, 2002), and shown that the dominance of the P1 peak the pattern of low spatial frequency is preferred (Kuba, Kubova, Kremlaček, & Langrova, 2007), as it can also be seen from our results (Figure 7).

GENERAL DISCUSSION

In Experiment 1, we asked observers to judge the temporal order of two perceptual events, a short auditory signal and an instant colour-change of a moving object. The parameters of auditory stimulus were kept constant through the experiment, assuming that time required to notice it does not change. From our previous reaction time studies we knew that that time required to detect change in colour decreases as velocity increases. We had a rightful expectation that in the temporal order judgment tasks we can also observe a similar temporal shift in the relation to acoustical signal as velocity of the moving object increases. In reality, the temporal interval between the perceived moment of colour-change and occurrence of the reference signal did not depend on the velocity of the moving object.

However, surprisingly, the time observers spent to give answers about temporal order of two events decreased with an increase of velocity of a moving object. It is important to remember, that we did not give any particular instruction how slow or fast to answer. Most certainly there was no pressure to answer as quickly as possible. Nevertheless, decision times reflected quite accurately the velocity of the moving object: the decision time decreases as velocity of the object increases. It is also relevant to notice that the shortening of the decision time with the increase of velocity occurred in the both cases, whether the acoustical signal was presented before the colour-change or after. These results indicate a disparity between perceptual (perceiving temporal order of events) and time required to give an answer, suggesting that they have different underlying decision processes.

We are not aware of many studies where perceptual decisions and time needed to make these decisions tell quite different stories. The decisions, in spite of their irregularity, were insensitive to velocity while time consumed to make these decisions demonstrated a clear dependence of velocity. In general, there is no obligatory relationship between decisions and time to make these decisions. Indeed, it is possible to imagine a measuring instrument in which measurement is not related to time required to produce this measurement. For example, it is not necessarily so that it takes more time to produce the final result for a voltmeter as the input voltage increases. Dependent on the exact measurement procedure, the measurement time may be independent on the magnitude of the measured attribute and any other physical attribute what might affect the measurement outcome.

Although there is no logical contradiction between TOJ and time required to give TOJ, a discrepancy exists between results provided by TOJ and RT experiments. Researchers have repeatedly noticed that RT and TOJ estimates to the perceptual lag are slightly different (Roufs, 1974). When perceptual lag is measured dependent of the stimulus intensity the RT estimates increase more rapidly with the decrease of intensity compared to other procedures. In the current situation the outcome is more radical: RT procedure reveals shortening the detection time dependent of the stimulus velocity while with the TOJ procedure we were not able to observe the influence of velocity at all. This may suggest that RT and TOJ are based on different perceptual representations. It is logical to expect that in the RT experiment the response is delivered as soon as the representation of the relevant event has reached the conscious threshold. For some not well understood reason the colour-change in a fast moving object reaches consciousness earlier than information about the exactly same change in a slow-moving object. However, when the observer is instructed to make a decision about the relative order of two perceptual events she may relay on some other information, not necessarily the time moments when events become for the first time available in the consciousness. It is possible that introspection, which is the main tool for evaluating temporal order of two perceptual events, does not have an access to fine temporal information which is required to estimate exact time when something enters our subjective awareness. It may be so that the temporal order is judged on the basis some other information, for example when the representations of the two events have reached maximal distinctiveness. One cannot exclude, for example, a possibility that there is a general tendency to perceive two temporally proximate events as perceptually simultaneous. 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, Johnston & Nishida, 2005). In other words, unlike RT temporal order judgements do not reflect differential neural delays for different sensory attributes. Similar conclusion was reached by Nishida and Johnston (2002) who proposed that that the perception of the relative time of events is based on the relationship of representations of temporal pattern that 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 match 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.

In this experiment we also had two different tasks – one was to track the visual stimulus, other to fixate the fixation point during the trials. The effect of velocity to the time spent on formulating and giving answers appeared in both conditions. That might suggest that the effect, repeatedly shown in previous study, is induced by the physical rather than retinal velocity of a moving object. Although the difference was very small it took slightly more time to give an answer in the tracking condition which may suggest that the subtraction of self-movement from the physical movement takes some additional time.

Still, the problem of previous study and Experiment 1 in this study, is the spatial and temporal uncertainty. The constantly changing position of moving object in space gives information about the duration time of this object and this prepares observer to be more and more ready to give a response, since the probability of expected event is increasing.

Nevertheless, when trying to reduce the spatial uncertainty by using areas fixated in space and filled with stationary or moving sinusoidal grating as a colour-changing stimulus both in TOJ and RT task the results showing no effect of velocity, were unexpected. The task here was similar we used in our previous study (Kreegipuu et al, 2006). Only, here we used stimuli having fixated spatial position, its luminance increasing and decreasing periodically. When using a moving bar as a stimulus the RTs to its colouration decreased with an increase of velocity in our previous study, but here using the grating to measure RTs to its colour-change, it does not. We were not expecting the effect of velocity to be as large found previously, since velocities used here where slower. Still, when carrying out few extra series with higher velocities (12.24 and 24.48º/s) for better comparison with the previous study, the results remained same.

One explanation might be that would be concluded that the critical aspect that determines whether times needed to detect colour-changes are dependent of velocity or not, is the presence of recognizable features that sinusoidal grating does not have. For example, when the moving object is a single bar, it has an edge and the position of this edge or peak is constantly changing in space. Berry and co-authors have shown illustratively that a moving bar elicits a moving wave of spiking activity in the population of retinal ganglion cells and the population activity travels near the leading edge of the moving bar (Berry, Brivanlou, Jordan, & Meister, 1999). If we have a sinusoidal grating area which luminance is periodically increasing and decreasing we, actually do not have any identifiable parts/features which spatial position would change on retina, here the projection on retina is constantly overwritten.

Another possible explanation why colour-change of moving grating does not show velocity-dependency, is that this overwriting of retinal image in the moment of colour-change happens in so short time that it is masking the last position of sine wave and by that making it harder to notice or not noticeable at all. For example, when the grating in condition of the highest spatial frequency (Experiment 4) is moving with velocity 9.2 °/s, the retinal image is overwritten 6 times in a second, which means after every 16.6 ms, at the same time when in the condition of lowest spatial frequency and velocity 9.2 °/s, the retinal image is overwritten after every 166ms. Although, the time between over writings here is longer than 100 ms (Smithson, & Mollon, 1999) that is usually referred as the maximum time between two stimuli for backward masking to appear, here also the colour-change as a distracting factor takes place inside that time period.

In conclusion, present study demonstrates two main results. First, the disparity between RT and TOJ tasks that is probably due to differences in decision-making mechanisms, as temporal order of events requires somewhat different representation than just detecting an event. Second, the velocity-dependence shown in previous study appears to be referable to certain stimulus' properties, like the constantly changing spatial position of a single moving stimulus, and seems to disappear when this information is not presented, as in the case of area of moving sinusoidal grating.

Acknowledgements

I am grateful to my supervisors Kairi Kreegipuu and Jüri Allik for their help and guidance. I also want to thank Aire Raidvee for programming and Maria Tamm and Nele Kuldkepp for their support and useful advice.

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