

# Temporal and spatial characteristics of attention to facilitate manual and eye-movement responses

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**Abstract.** Previous investigation found that the speed of saccadic eye movements is enhanced when a temporal interval (gap) is introduced between the disappearance of a foveal fixation mark and the appearance of a peripheral target (the gap paradigm). Attention was shown to be involved in the gap paradigm. Here, we investigated relevant temporal and spatial characteristics of attention, manipulating central fixation marks and peripheral targets. Results from three experiments indicate that (i) the speed of manual and eye-movement detection is accelerated when a fixation mark changes abruptly (in less than 100 ms) before its termination in the gap paradigm; (ii) the speed is further accelerated when a peripheral target location is pre-cued; (iii) sufficient time for fixation (1000 ms) is necessary for the facilitation. These results suggest that fast and transient attention at the fixation spot facilitates attentional disengagement process that urges a spatial-orienting mechanism. Sustained attention is required in the engagement process during the fixation.

## 1 Introduction

### 1.1 *Attention and eye movements*

The relationship between selective spatial attention and eye movements has been the subject of speculation over the years. As early as the 19th century, Helmholtz (1867/1962) observed an advantage of a spatially attended locus for recognizing letters in the peripheral visual field without a shift of gaze. This observation suggested a mechanism of spatial attention that can operate independently of eye movements. However, it is only recently that truly objective research on attention has been embarked upon (Eriksen and Hoffman 1972; Bashinski and Bacharach 1980; Posner 1980; Remington 1980). Posner and his colleagues (Posner 1974, 1978; Posner et al 1980) devised a visual cueing paradigm to investigate a spatial aspect of attention. A visual cue was presented at one side of the peripheral visual field, followed by a target presented at the same or the opposite side. Spatial attention was evaluated by examining the positional relationship between cue and target. Fixation was maintained at the central spot, in an attempt to dissociate attention from eye movements. Using this paradigm, Posner (1980) discovered a component of attention independent of eye movements. The speed of detection, measured as reaction time (RT), was facilitated at the pre-cued ('valid') side of the visual field, as compared to the opposite ('invalid') side, even though eyes were fixated at the central spot. The allocation of attention in the absence of eye movements was referred to as 'covert orienting', and distinguished from 'overt orienting', which involves oculomotor responses such as saccadic eye movements. In order to explain the dynamic aspect of attention, Posner et al (1984) proposed a three-step processing model of movement (shift) of attention: attentional engagement, disengagement, and re-engagement. According to their claim, attention is first attracted to one spatial location where

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visual stimulus is presented (engagement). Next, it ought to be released to move toward other locations when the stimulus disappears (attentional disengagement). Finally, attention is re-engaged by a novel visual stimulus appearing at a different location. The limited spatial range of focal attention, often described as a 'spotlight' metaphor, was found to move quite rapidly. At least 50–100 ms was necessary for attention to shift from a central fixation spot to a target at a distance of 8 deg (Sagi and Julesz 1985), while 180–200 ms was found to be necessary for normal saccadic eye movements to be activated (Fischer and Ramsperger 1984).

### 1.2 *Express saccades*

In the literature on saccades, there have been occasional findings of the shortening of saccadic latency. Saccadic responses are facilitated when a temporal gap or interval is introduced between fixation offset (disappearance) and target onset (appearance) (Saslow 1967). Using this paradigm, Fischer and his colleagues found extremely rapid eye movements with latencies of 80–120 ms, which are referred to as 'express' saccades (Fischer and Boch 1983; Fischer and Ramsperger 1984). To explain this phenomenon, Fischer and Breitmeyer (1987) put forward the attention-disengagement hypothesis. First, attention is assumed to be engaged at the fixation spot. Then, it is disengaged when the fixation mark disappears. When a visual target appears, attention shifts to a target location and re-engages at the new target. This attentional shift requires rapid saccadic eye movements. Mackeben and Nakayama (1993) explicitly tested this hypothesis by examining the time course of Vernier discrimination performance. Using a spatial cueing paradigm combined with backward masking (Bergen and Julesz 1983; Sagi and Julesz 1984), they found that attention shifted very rapidly within 100 ms from the fixation removal without eye movements in the gap condition, yielding improved Vernier discrimination performance at the cued location. The course of this improvement was much slower when fixation was not terminated ('overlap' condition). The fast time course of facilitation overlaps that of express saccades. Maximal facilitation was observed with a gap duration of 200 ms (Mayfrank et al 1986), suggesting that attention and express saccades are highly correlated. Several other studies have been conducted that attempted to dissociate the locus of visual attention from that of visual fixation (Kingstone and Klein 1993; Tam and Stelmach 1993). These experiments showed that removing the central fixation stimulus resulted in shorter latencies whether the central fixation stimulus was attended or not.

### 1.3 *Components of attention*

Although it now becomes evident that attention can be involved in the generation of express saccades, the developmental process of attention before eye movements is still unclear. In the present study, we have investigated temporal and spatial properties of attention, namely its disengagement processes during the course of fixation changes. As noted, attentional disengagement is very rapid, being completed within 50–100 ms after the fixation offset (Mackeben and Nakayama 1993). The time course of this rapid process coincides with that of a transient component of attention that develops within 100 ms. This component operates in an involuntary, compulsory, and a stimulus-driven manner, suggesting an involvement of early visual processing (Sagi and Julesz 1985; Nakayama and Mackeben 1989; Hikosaka et al 1993a). Here, we assume that the transient component of attention and the disengagement process are tightly linked. Then, one prediction is that the transient component urges or reinforces the disengagement process to be activated more vigorously and induces rapid shifts of attention. Experiment 1 was designed to test this hypothesis by manipulating the transient component of attention at the locus of fixation. A summary of the results was presented elsewhere (Shimojo and Tanaka 1994).

## 2 Experiment 1: Transient signals facilitate attentional disengagements

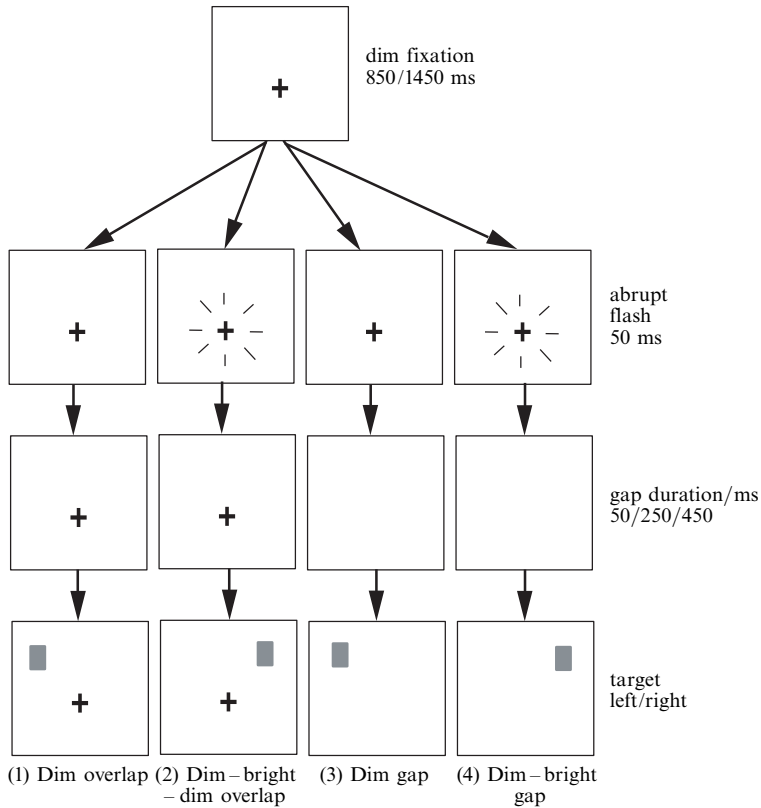
In the first set of experiments, we tested whether a change of the transient signal at the fixation spot before its offset facilitates the attention-disengagement process and accelerates responses. An abrupt signal (duration 50 ms) was given to the fixation mark before its termination. Different dimensions of visual features such as luminance, color, and orientation were used for the abrupt change. Three sub-experiments were designed accordingly for the change, which will be referred to as the luminance experiment, the color experiment, and the shape experiment, respectively. We expected a similar facilitation across different dimensions assuming that abrupt signals attract attention in an involuntary and stimulus-driven manner (Müller and Rabbitt 1989; Remington et al 1992). Manual responses (a button press without eye movements) and saccadic eye movements were both tested.

### 2.1 Methods

**2.1.1 Stimuli.** Stimuli consisted of a  $0.2 \text{ deg} \times 0.2 \text{ deg}$  fixation cross and a  $0.6 \text{ deg} \times 0.6 \text{ deg}$  target square. The distance between the fixation and the target stimuli was  $11.0 \text{ deg}$ , and the distance between the left and the right target stimuli was  $19.3 \text{ deg}$ . The luminance of the target was  $2.58 \text{ cd m}^{-2}$  with a background luminance of  $0.01 \text{ cd m}^{-2}$ . In the luminance experiment, the fixation cross was either gray (referred to as 'dim',  $0.34 \text{ cd m}^{-2}$ ), or flashed (referred to as 'bright',  $8.13 \text{ cd m}^{-2}$ ). In the color experiment, the fixation was  $0.5 \text{ deg} \times 0.5 \text{ deg}$  square, and its color was either red [ $0.53 \text{ cd m}^{-2}$ , hue (0.33, 0.56)] or green [ $0.22 \text{ cd m}^{-2}$ , hue (0.62, 0.26)]. The luminances of red and green in this and the following experiment were adjusted to be close to equiluminance as possible by the minimum flicker method (Wagner and Boynton 1972). In the orientation experiment, the fixation was a gray ( $0.34 \text{ cd m}^{-2}$ ) rectangle measuring  $0.15 \text{ deg} \times 0.50 \text{ deg}$ , elongated either in the vertical or the horizontal direction. Stimuli were presented on a cathode-ray-tube (CRT) display (Commodore 1840S, noninterlaced; frame frequency 60 Hz). Stimulus presentation, timing control, and data acquisition were performed by a microcomputer (Amiga 1200; Commodore) with the Amiga disc operating system.

### 2.1.2 Experimental procedures

In the luminance experiment, there were two major conditions: the 'overlap' condition where the fixation stimulus was kept on, and the 'gap' condition where the fixation stimulus was extinguished. These conditions were extended by adding an abrupt signal change to the fixation mark (duration 50 ms), producing the following conditions: (1) dim overlap, (2) dim-bright-dim overlap, (3) dim gap, and (4) dim-bright gap (see figure 1). Similarly, four conditions were used in the color experiments: (1) green overlap, (2) green-red-green overlap, (3) green gap, and (4) green-red gap. In the orientation experiment, they were (1) vertical overlap, (2) vertical-horizontal-vertical overlap, (3) vertical gap, and (4) vertical-horizontal gap. A trial started with an inter-trial interval of 500 ms. In the luminance, color, or orientation experiment, either a dim, green, or vertical fixation stimulus was presented in the center of the screen for 850 or 1450 ms (durations randomly chosen). This duration was referred to as interstimulus interval (ISI). The fixation stimulus turned either bright, red, or horizontal for 50 ms in conditions 2 and 4 (fixation changed), or remained dim, green, or vertical in conditions 1 and 3 (fixation unchanged). This duration was determined on taking account of the time course of the transient component of attention (Nakayama and Mackeben 1989). For the next period, referred to as gap duration, which was randomly chosen from 50, 250, or 450 ms, the fixation stimulus became either dim, green, or vertical again (conditions 1 and 2), or was extinguished (conditions 3 and 4). The four conditions were counterbalanced. Note that condition 2 was set especially to examine timing or warning effects caused by the transient signal (Ross and Ross 1981; Reuter-Lorenz et al 1991; Jüttner and Wolf 1992). If transient changes serve only as a



**Figure 1.** Schematized diagram of the luminance experiment (experiment 1). Four conditions were randomly mixed in a session: (1) dim-overlap, (2) dim-bright-dim-overlap, (3) dim-gap, and (4) dim-bright-gap conditions. A transient flash (50 ms) was given to the fixation cross in conditions 2 and 4. Only one gap duration from 50, 250, or 450 ms was chosen on each trial. Target location (left or right) was randomized. Each condition contained 20% of catch trials where no target stimuli were presented.

warning or alertness signal, then responses in both gap and overlap conditions should be equally facilitated. The target was presented at the top-left or the top-right of the fixation mark (randomly chosen) and remained until detected. Subjects were seated at a distance of 57 cm from the display, and asked to maintain fixation and to detect the peripheral target as fast as possible (simple detection task). Reaction time (RT), measured by a button press, was defined as the time between the onset of target and the onset of response. Catch trials, where no target was presented, were employed in 20% of the trials (counterbalanced) to ensure that the subjects responded to target appearance, but not to the transient fixation change (Jüttner and Wolf 1992). There were four types of catch trials in the luminance experiment: (1) dim-overlap catch, (2) dim-bright-dim-overlap catch, (3) dim-gap catch, and (4) dim-bright-gap catch. Similar catch trials were employed in the color and orientation experiments. Feedback was given to catch trials when the subject pressed the button too fast ( $RT < 700$  ms). The viewing condition was binocular and the head was stabilized by a chin-rest. Eye fixation was monitored in selected sessions by Ober 2 eye-tracking system (Permobil Corp., Timra, Sweden). The temporal resolution was 120 Hz. The spatial resolution was measured and the minimum accuracy was found to be 18 min of arc. The subject was dark-adapted for 2 min before the experiment. A practice session (100 trials) was employed in the initial session.

**2.1.3 Subjects.** Four observers participated in each sub-experiment in this and following experiments, unless mentioned otherwise. The observers, except YT and SS (the authors), were students of the Massachusetts Institute of Technology (aged 22–27 years), who did not know the purpose of the experiments. The authors were highly experienced with the paradigm described here. All subjects had normal or corrected-to-normal visual acuity and normal color vision.

**2.1.4 Data analysis.** In each sub-experiment, data were analyzed with respect to four conditions, three gap duration periods, and two target locations. Each was repeated twenty times, so that the total number of trials was 480 ( $4 \times 3 \times 2 \times 20$ ) for each subject. RTs below 100 ms and above 1300 ms were eliminated from the analysis. In the saccadic eye-movement task, the accepted range was 50–1300 ms. Sessions in which the false-alarm rate (erroneous responses in the catch trials) exceeded 10% were eliminated. The data from each subject were combined for a three-way repeated-measures analysis of variance (ANOVA; condition  $\times$  gap duration  $\times$  location) in each sub-experiment.

## 2.2 Results

In the luminance experiment, no sessions were excluded because all subjects exceeded 90% of correct performances. Averaged correct response was 96%. The differences in false-alarm rates in the catch trials were negligible (see table 1). This trend was common to all experiments reported here (table 1) and will not be mentioned later. Eye fixation was monitored during the selected session, and found to be maintained within a limited range (less than 30 min of arc from the central fixation cross). Repeated-measures ANOVA shows the significant main effects of condition, gap interval, and their interaction (see table 2). Because no difference was found between two locations ( $F_{1,24} < 1$ ), data were pooled in terms of location. This tendency was identical for the luminance, color, and orientation experiments. RTs averaged across four observers were plotted as a function of gap duration (see figure 2a). As is clearly seen, two gap conditions (dim gap and dim–bright gap) produced shorter RTs at all gap durations compared with two overlap conditions (dim overlap or dim–bright–dim overlap). The shortest responses were found at the gap duration of 250 ms. This is a typical gap effect found in the literature. Within the gap conditions, the dim–bright-gap condition produced shorter RTs (mean  $\pm$  SE,  $57 \pm 18$  ms,  $p < 0.01$ ) compared with those in the dim-gap condition. On the other hand, no difference was found between the dim-overlap and the dim–bright–dim-overlap condition ( $17 \pm 45$  ms,  $p > 0.05$ ). The tendency was similar in the color experiment and the orientation experiment. Clear gap effects were found in both the green-gap and green–red-gap conditions (see figure 2b) as well as the vertical-gap and vertical–horizontal-gap conditions (five subjects, figure 2c). Moreover, RTs were

**Table 1.** False-alarm rates in catch trials ('t' denotes 'transient' conditions (ie 'dim–bright')).

Experiment	Overlap/%	t-Overlap/%	Gap/%	t-Gap/%	Overall/%
Experiment 1					
luminance	4.1	4.2	3.8	3.9	4.0
color	5.5	4.6	5.7	4.9	5.1
orientation	5.0	3.6	3.7	5.3	4.5
eye movement	3.0	3.6	3.7	4.1	3.6
Experiment 2					
peripheral	2.6	2.9	3.1	3.4	3.1
whole flash	4.7	4.6	4.7	5.3	4.9
Experiment 3					
gap	2.2	2.1	1.7	2.0	2.1
initial fixation	4.5	3.5	3.7	4.3	4.0

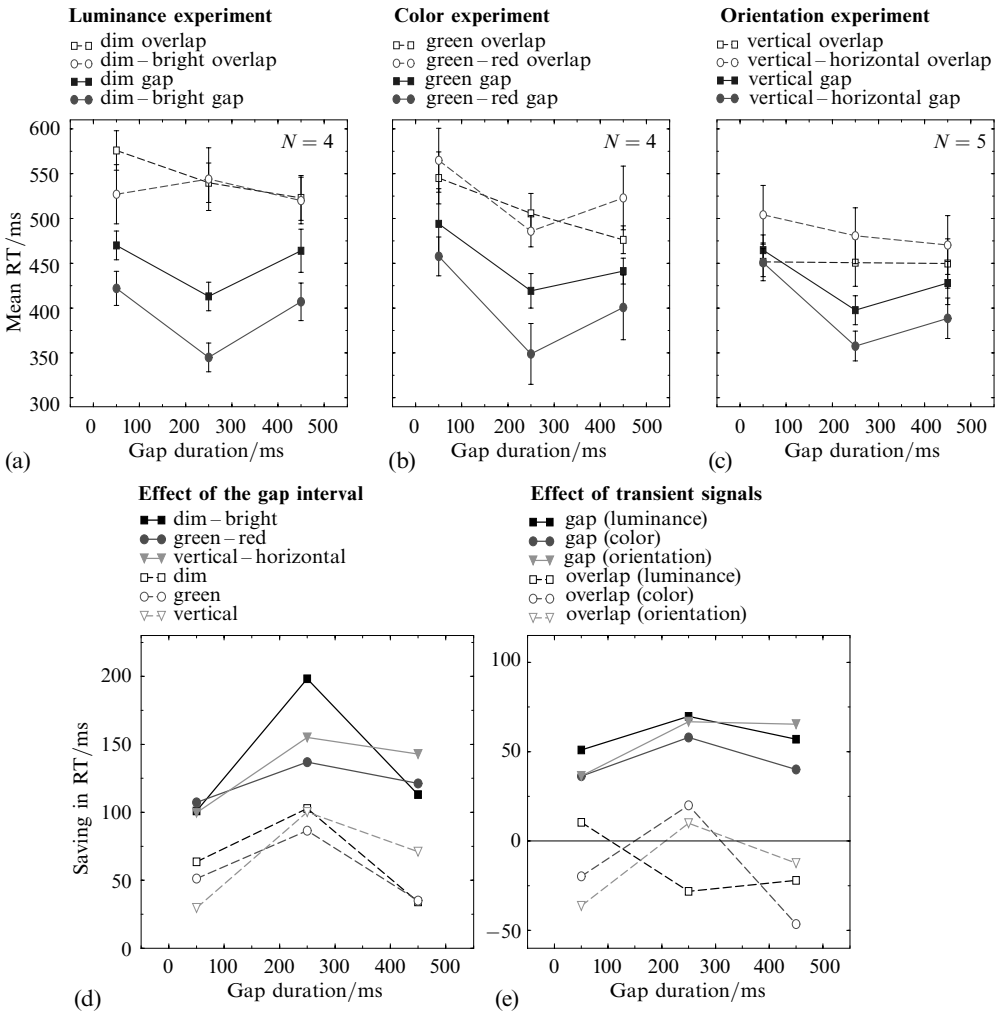
**Table 2.** Summary of analyses of variance of experiment 1.

Task factor	<i>F</i>	<i>p</i>
Luminance experiment		
condition	26.79	0.0001**
gap duration	8.27	0.001**
condition $\times$ gap	2.17	0.05*
Color experiment		
condition	15.44	0.0001**
gap duration	14.16	0.0001**
Orientation experiment		
condition	21.68	0.0001**
gap duration	16.81	0.0001**
condition $\times$ gap	3.53	0.01**
Eye movements		
condition	26.41	0.0001**

Note: Data were analyzed with a three-way repeated-measures analysis of variance for each sub-experiment. Only the main effects and interactions that were significant are given.  
\* $p < 0.05$ , \*\* $p < 0.01$

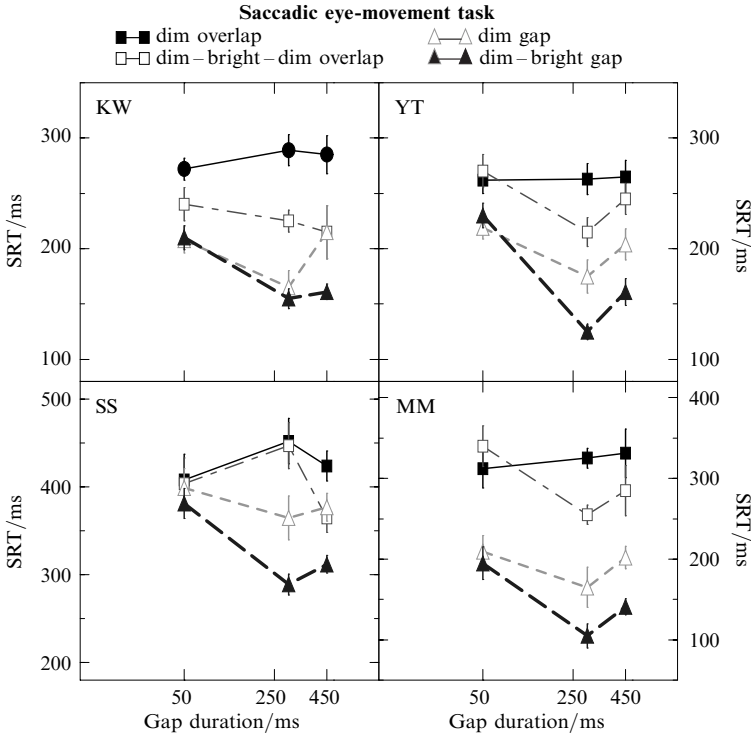
shortest in the green–red-gap and vertical–horizontal-gap conditions, respectively. The shortest RTs were found at the gap duration 250 ms in both experiments in the gap tasks. To evaluate the magnitude of the gap effect, a saving in RTs in the gap condition over the overlap condition was calculated and plotted against gap duration (figure 2d). Transient signals at the fixation (luminance, color, and orientation) produced greater savings in RTs than without transient signals. The average saving in RTs with transient signals in the luminance experiment (referred to as ‘dim–bright’ in the graph) was  $137 \pm 33$  ms, compared with  $66 \pm 29$  ms without transient signals (‘dim’). Similar tendencies were observed in the color and orientation experiments. RT savings were  $120 \pm 42$  ms versus  $57 \pm 31$  ms in the color experiment, and  $115 \pm 21$  ms versus  $63 \pm 32$  ms in the orientation experiment, with and without transient signals, respectively. Note that the peak in saving was observed in the gap duration of 250 ms both with or without transient signals, suggesting an involvement of a process common to both gap tasks. We also evaluated the effects of the transient signal change for gap and overlap tasks, respectively (figure 2e). A saving in RTs, the difference in RT between the dim-gap and the dim–bright-gap conditions for example, is plotted for each gap duration (figure 2e). Similar calculations were also done for overlap conditions. Only gap tasks showed a significant saving in RTs ( $55 \pm 15$  ms,  $67 \pm 19$  ms, and  $45 \pm 13$  ms, in the luminance, color, and orientation experiments, respectively, all  $ps < 0.01$ , paired *t*-test), whereas no saving was found in the overlap tasks in each sub-experiment ( $-11 \pm 15$  ms,  $-16 \pm 25$  ms,  $-13 \pm 10$  ms, all  $ps > 0.05$ , respectively, paired *t*-test). Significant advantage was observed at the gap duration of 250 ms in some of the overlap tasks (both color and orientation experiments), compared with other gap durations. This might be due to the effect of learning a specific timing sequence (Fischer and Ramsperger 1986), because it was most evident with the experienced observer YT (data not shown).

**2.2.1 Saccadic eye movements.** To compare eye movements with manual responses, the reaction times of saccadic eye movements were measured. Subjects were instructed to foveate a peripheral target as fast and as accurately as possible. Saccadic reaction time (SRT) was defined as the time from the target onset to the initiation of the saccadic eye movement. Eye blinks were selected on inspecting the raw data and taken out from the analysis. Results indicate a clear gap effect. SRTs were shorter in both gap



**Figure 2.** Experiment 1. Results of the luminance, color, and orientation experiments. Data were combined across subjects. (a)–(c) Mean RTs are plotted for each sub-experiment against gap duration. Vertical bars in these and succeeding graphs indicate standard errors of mean. (d) RTs re-calculated to demonstrate the gap effect. Savings in RT are plotted showing the difference between gap and overlap conditions. (e) RTs re-calculated to demonstrate the effect of transient changes. Savings in RT are plotted showing the difference between the presence and absence of transient signals at the fixation mark.

conditions compared with those in the overlap conditions, with a ‘dip’ at the gap duration of 250 ms (figure 3a). We regard this as a modified form of express saccades (Fischer and Boch 1983; Fischer and Ramsperger 1984) because of the following reasons: (1) the SRTs are relatively shorter (150–170 ms) compared with overlap conditions; (2) the shorter SRTs were observed only at the limited gap duration (250 ms), consistent with the literature (Mayfrank et al 1986). Note that the range of latencies was longer than that of the original express saccades [Fischer and Ramsperger (1983) 100–140 ms]. This is possibly due to: (i) the different distance tested (11.0 deg in the current study as opposed to 4.0 deg in the previous studies); (ii) the introduction of temporal uncertainty by randomizing intervals; and (iii) the introduction of spatial uncertainty by randomizing target locations. In the dim–bright-gap condition, SRTs were even shorter than those in the dim-gap condition, with a magnitude of  $40 \pm 12$  ms, consistent with manual



**Figure 3.** Results of the saccadic eye-movement task in experiment 1. SRT is plotted against gap duration. Each subject shows a clear gap effect. Furthermore, latencies were further facilitated in the dim-bright-gap condition (see text in detail).

responses described above. The SRTs for subjects MM and YT (100–120 ms) were as short as the original express saccades (Fischer and Ramsperger 1984), despite the larger target distances tested (11.0 deg). The same two subjects showed a reduction in SRTs at the gap duration of 250 ms ( $p < 0.01$ ) in the dim-bright-dim-overlap condition, probably due to the learning of timing such as observed in the color and orientation experiments. The SRTs of one subject (SS) were somewhat longer (280–450 ms) than those of other subjects, although the overall pattern of results was similar.

### 2.3 Discussion

The results of this experiment demonstrated three aspects: (i) An addition of a transient component at the fixation spot facilitated both manual and eye movement responses. (ii) This facilitation was evident only when the fixation was removed (gap condition). (iii) Different dimensions of visual features (luminance, color, or orientation) composing the transient change did not affect the trend of facilitation. Here, we compared saccadic eye movements and manual responses using highly compatible stimuli. Similar pattern of results—facilitation in the gap task and its further enhancement with transient fixation signals—was observed. This suggests an involvement of a common functional mechanism, namely an attention mechanism. One may speculate that transient alternation of fixation marks served as a general timing cue or a warning signal (Posner and Boies 1971; Ross and Ross 1981; Reuter-Lorenz et al 1991; Jüttner and Wolf 1992; Tanaka and Sagi 2000). To address this question, RTs were compared between gap and overlap conditions when both contained transient changes (conditions 2 and 4). Considering that additional transient signals produced an RT reduction (saving) in the gap condition whereas no reduction was found in the overlap condition, it seems unlikely that only timing or warning signals were responsible for the facilitation (Ross and Ross 1981;

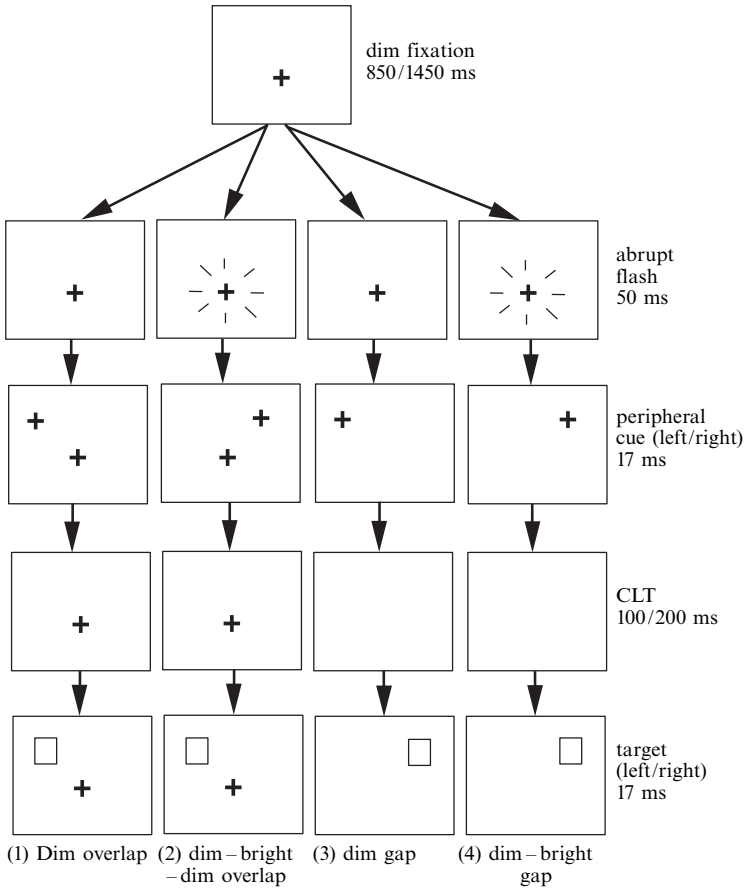
Reuter-Lorenz et al 1991). However, there was a common tendency that RTs were shorter with gap durations of 250 ms in conditions 2, 3, and 4 where timing cues were equally given to the fixation mark. We attributed this to the learning effect of the specific timing; however, it was not clear how attention was involved in this specific timing sequence. To test the involvement of attention more directly, we evaluated spatial aspects of attention in the next experiment. Attention has been regarded as showing 'spotlight' type of characteristics, ie reduction of RTs in detection, and reduction of thresholds in discrimination was observed when a location was pre-cued, where attention was properly directed (Bashinski and Bacharach 1980; Posner 1980). We used this paradigm in experiment 2. Attention was driven by a peripheral visual stimulus (cue) in an automatic, compulsory, and stimulus-driven manner (endogenous covert attention). If timing/warning signals are critical—thus the abrupt changes are irrelevant to location—then the reduction in RTs would be homogeneous across locations. In contrast, if the abrupt change at the fixation spot is critical to spatial attention, then RTs would be different at different locations.

### 3 Experiment 2: Spatial aspects of attention

In this experiment, the involvement of attention in the fixation stimulus was tested by manipulating spatial factors (Posner 1980; Kingstone and Klein 1993; Tam and Stelmach 1993). The first set of experiments, referred to as the peripheral cueing experiments, was employed to directly assess the involvement of attention by using the cost–benefit paradigm (Posner 1980; Nakayama and Mackeben 1989; Kingstone and Klein 1993). In this paradigm, spatial selective attention can be quantified by a 'benefit' (ie saving of RT) at a pre-cued location, accompanied with a 'cost' (increase of RT) at non-cued locations. We assumed that spatial attention was involved during the transient fixation change and its termination. If so, the facilitation ('benefit') should be specific to the pre-cued location in the dim–bright-gap condition rather than in the dim–bright–dim-overlap condition. In contrast, if there was no 'benefit' at the pre-cued location in the dim–bright-gap condition, that would argue for the warning/timing hypothesis, where 'benefit' is general and independent of location. The second set of experiments, referred as the whole flash experiments, was employed to determine whether the facilitation when using additional signals stemmed from local transient components (fixation change) or global timing signals independent of location (Mackeben and Nakayama 1993). Assuming that spatial selective attention operating an 'exogenous' orienting mechanism is involved, we expected that only the local fixation change was responsible for the facilitation, producing a reduction in RTs.

#### 3.1 Procedures

In the peripheral cueing experiment, conditions similar to experiment 1 in terms of fixation manipulation (dim/bright  $\times$  overlap/gap) were tested (see figure 4). The time course of one trial was as follows: after 500 ms of blank period (intertrial interval) a dim fixation mark appeared for either 850 or 1450 ms (randomly chosen duration). Then, the fixation mark flashed for 50 ms (bright fixation) in conditions 2 and 4, whereas it remained 'dim' in conditions 1 and 3. Immediately after that, a cue was presented briefly (17 ms) at a possible target location (top-left or top-right, randomly chosen) at a distance of 11.0 deg from the fixation mark with the dim fixation cross (overlap, conditions 1 and 2) or without (gap, conditions 3 and 4). The cue disappeared and only blank field with (conditions 1 and 2) or without (conditions 3 and 4) the fixation followed for 100 or 200 ms (randomly chosen duration). This period is referred to as cue lead time (CLT). This duration was determined considering both gap durations of express saccades [maximal around 150–200 ms; Fischer and Boch (1983)] and time course of covert attentional shifts [maximal with CLT of 100 ms; Posner and Cohen (1984)]. The peripheral cue was a



**Figure 4.** Schematized diagram of the peripheral-cueing experiment (experiment 2). Conditions similar to experiment 1 were tested with additional transient peripheral cues (17 ms) at the top-left or top-right (randomized) of the fixation cross, followed by the cue lead time (CLT). Target was presented at top-left and top-right (randomized), composing ‘valid’ (same cue–target location) and ‘invalid’ (different cue–target location) trials. Each condition contained 20% of catch trials where no target stimuli were presented.

cross, the same shape, size, and luminance as the fixation stimulus. After the CLT, a target was presented at the same or at the opposite side from the cue. The location relationship between cue and target was counterbalanced between left–left, left–right, right–left, and right–right. The left–left and right–right pairs were referred to as valid, while the left–right and right–left pairs were referred to as invalid (Posner 1980). To minimize possible forward-masking effects, we used a gray line-drawn square as the target (size: 2 deg  $\times$  2 deg) with an inner area blanked. The cue (cross: 0.2 deg  $\times$  0.2 deg) appeared in the center of the square; thus there was no spatial overlap between cue and target. To minimize effects of eye movements as well as possible masking effects, both cue and target durations were set as short as 17 ms. Catch trials were employed in each condition in both experiments (see experiment 1). In the peripheral cueing experiment, data were analyzed with respect to the 4 conditions (including 20% of catch trials), 2 CLTs, 2 locations, and 2 cue–target relationships (‘valid’/‘invalid’, termed validity). Each cell was repeated 12 times; thus the total number of trials was 384 (4  $\times$  2  $\times$  2  $\times$  2  $\times$  12) for each subject. Data were combined across subjects and analyzed by a four-way repeated-measures ANOVA (conditions  $\times$  CLT  $\times$  location  $\times$  validity). Other procedures were the same as experiment 1.

In the whole flash experiment, an entire field of display extending over  $19 \text{ deg} \times 27 \text{ deg}$  was manipulated. The original color of the screen was green [hue: (0.33, 0.56); luminance:  $0.53 \text{ cd m}^{-2}$ ]. This turned red [hue: (0.62, 0.26); luminance:  $0.22 \text{ cd m}^{-2}$ , equiluminant] for 50 ms, and turned green again during the gap duration. The luminance of the target was set at  $8.13 \text{ cd m}^{-2}$ , higher than that in experiment 1 to compensate for a possible forward-masking effect from the red background. The following four conditions were compared: (1) dim-background red (termed bkgred)-dim overlap, (2) dim-bright-dim overlap, (3) dim-bkgred gap, and (4) dim-bright gap. A comparison between conditions 3 and 4 allowed us to test whether the RT reduction was specific to the locus of fixation or whether it was based on general timing/warning effects independent of location, because this experiment contained the same timing cues in all conditions and the only difference was a spatial aspect of the transient changes. Therefore, if the timing/warning signal is the main factor, all conditions should lead to identical results. On the contrary, if spatial attention is involved, results should differ between conditions. Four subjects participated in each sub-experiment.

### 3.2 Results

In the peripheral cueing experiment, the rate of the correct response was 97% in the catch trial. The ANOVA showed no differences in CLTs (between 100 and 200 ms,  $p > 0.05$ ) or in location ( $p > 0.05$ ); thus data were pooled in terms of CLT and location (table 3). In both the dim-gap and the dim-bright-gap conditions, RTs were significantly shorter in 'valid' than in 'invalid' conditions ( $72 \pm 35 \text{ ms}$ ,  $p < 0.01$ ; and  $96 \pm 31 \text{ ms}$ ,  $p < 0.001$ , respectively, see figure 5a), whereas there was no statistical difference between 'valid' and 'invalid' locations in both the dim-overlap ( $16 \pm 26 \text{ ms}$ ,  $p > 0.05$ ) and the dim-bright-dim overlap ( $27 \pm 38 \text{ ms}$ ,  $p > 0.05$ ) conditions. This indicates substantial 'benefit' in the gap conditions, with little 'benefit' in the overlap conditions (see figure 5b). Note that RTs were the shortest at the 'valid' location in the dim-bright-gap condition, suggesting that attention shifts were most enhanced in this condition. RTs in the dim-bright-gap condition were shorter than those in the dim-gap condition ( $34 \pm 10 \text{ ms}$ ,  $p < 0.001$ ), whereas RTs in the dim-bright-dim-overlap condition were identical to those in the dim-overlap condition ( $11 \pm 14 \text{ ms}$ ,  $p > 0.05$ ), suggesting that the transient component at the fixation spot produced a further RT reduction due to the 'valid' pre-cue in the gap task.

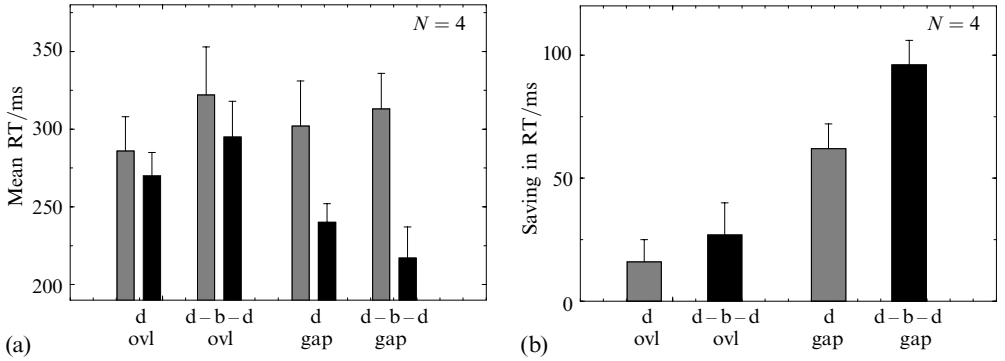
**Table 3.** Summary of analyses of variance of experiment 2.

Task factor	<i>F</i>	<i>p</i>
Peripheral experiment		
condition	18.35	0.01**
gap duration	8.25	0.01**
Whole flash experiment		
condition	16.13	0.0001**
gap duration	41.42	0.0001**

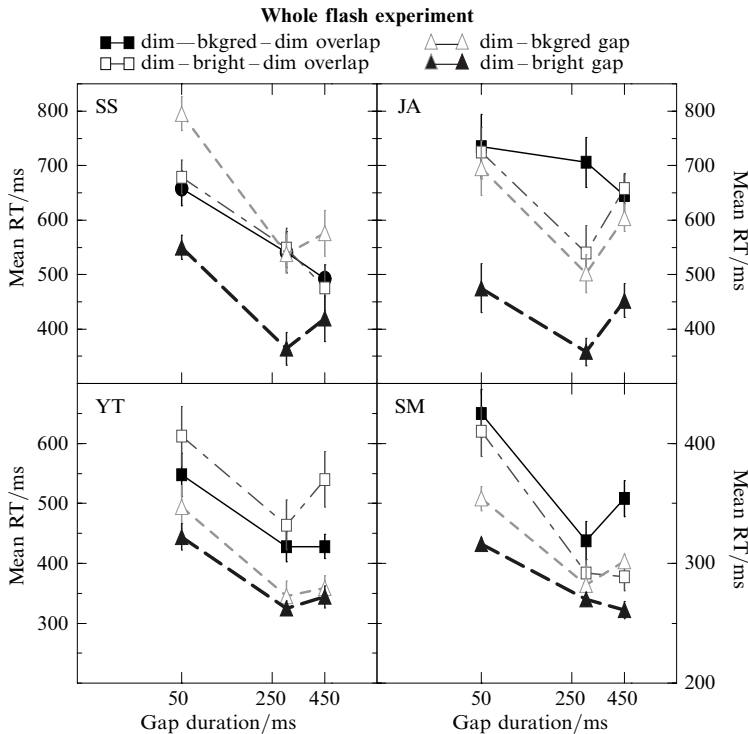
Note: Data were analyzed with a three-way repeated-measures analysis of variance for each sub-experiment. Only the main effects and interactions that were significant are given.

\* $p < 0.05$ , \*\* $p < 0.01$

In the whole flash experiment, the correct response rate was 95% in the catch trial. Mean RTs were shorter in the dim-bright-gap condition ( $124 \pm 24 \text{ ms}$ ,  $p < 0.001$ ; figure 6) compared with the dim-bkgred-gap condition. This is against the general-warning hypothesis, and argues for the spatial-attention hypothesis. The difference was rather small for two subjects (YT and SM) whose overall RTs were generally short (463 ms and 324 ms, respectively, compared with 551 ms for SS and 523 ms for JA), suggesting



**Figure 5.** (a) Results of the peripheral cueing experiment (experiment 2). Data are combined across subjects. Dark bars indicate mean RTs for the 'valid' (same) location, and light bars 'invalid' (different) location for each condition. RTs at the same location significantly reduced in both gap conditions. (b) Saving in RTs. The magnitude of 'benefit' (= saving in RTs) was much enhanced with 'gap' intervals, and maximal in the dim-bright-dim-gap condition. d ovl = dim-overlap, d-b-d ovl = dim-bright-dim-overlap, d gap = dim-gap, d-b-d gap = dim-bright-dim-gap conditions.



**Figure 6.** Results of the whole flash experiment (experiment 2). Mean RTs are plotted against gap duration. RTs were most reduced in the dim-bright-gap condition.

that timing of the background flash was learned. RTs in two overlap conditions (dim-bright-dim overlap and the dim-bkgred-dim overlap) were very similar, longer than those of the gap conditions, again inconsistent with the general-warning account: according to the hypothesis, the identical time course across all conditions should have resulted in identical RTs, which was not the case. Generally, RTs were long at the gap duration of 50 ms, reflecting possible forward-masking effects from the fixation or the background change (stimulus onset asynchrony,  $50 + 50 = 100$  ms). This is consistent with visual masking effects in the literature (Breitmeyer and Ganz 1976).

### 3.3 Discussion

In the whole flash experiment, both overlap conditions (conditions 1 and 2) yielded significantly longer RTs than those of the gap conditions (conditions 3 and 4). This rules out the general-timing/warning hypothesis (Ross and Ross 1981; Reuter-Lorenz et al 1991). Even though the time courses were identical, the RT reduction occurred specifically in the gap task with the local fixation change, but not with the global visual field change. This suggests that timing signals independent of location are not critical for the RT reduction. Instead, transient signals at a particular location (fixation spot) are critical to the effect. Results in the peripheral cueing experiment showed the 'benefit' for the cue towards target at the 'valid' location, providing direct evidence for the involvement of spatial attention in the RT reduction (Posner 1980; Posner and Cohen 1984; Mackeben and Nakayama 1993). The difference between the large 'benefit' in the gap conditions and the small 'benefit' in the overlap conditions is not compatible with the warning/alertness hypothesis, because, as we noted, this hypothesis predicted nonselective 'benefit' for both gap and overlap conditions. Results indicate, on the contrary, a significant 'benefit' in the gap conditions but much less 'benefit' in the overlap conditions. Furthermore, the 'benefit' was particularly enhanced with additional transient signals to the fixation/attention locus, suggesting again the involvement of attention. Another indirect evidence that rules out the timing/warning hypothesis was the absence of statistical difference ( $11 \pm 12$  ms) between the dim-overlap and the dim-bright-dim-overlap conditions. If the timing/warning hypothesis holds, the difference between these two overlap conditions should be as much as that between the dim-gap and the dim-bright-gap conditions ( $34 \pm 10$  ms), which was not the case. This is consistent with the results of experiment 1.

## 4 Experiment 3: Temporal aspects of attention

In the previous experiment, attention was assessed in space. In this experiment, temporal aspects of attention were addressed. In the first set of experiments referred to as the gap experiment, the duration of the transient fixation change was manipulated to find an optimal duration of the visual transient. In the second set of experiments referred to as the initial fixation experiment, the duration of the initial 'dim' fixation stimulus was chosen on the basis of either a transient (100 ms) or a sustained component (1000 ms) of attention (Nakayama and Mackeben 1989; Hikosaka et al 1993a). Attentional engagement/disengagement model predicts that spatial attention remains at the locus of fixation in the overlap condition, whereas it moves swiftly to a peripheral target position in the gap condition (Posner et al 1984; Fischer and Breitmeyer 1987). In other words, attention, which is first engaged at the locus of fixation, is 'released' with its termination (disengagement process). Our hypothesis is that initial engagement processes need time, requiring sustained attention (Mayfrank et al 1986; Nakayama and Mackeben 1989). Therefore, we expect that an involvement of the sustained component (1000 ms) during the initial fixation is necessary for the rapid disengagement process triggered by the transient fixation change and its removal. These two components would cause the maximal facilitation, producing fast responses.

### 4.1 Procedures

In the gap experiment, the stimulus configuration was identical to condition 4 (dim-bright gap) in experiment 1. The time course was identical, except that the duration of the brighter fixation was randomly chosen from either 17, 50, 100, or 400 ms on each trial, instead of the fixed duration of 50 ms. The gap duration (50/250/450 ms), the dim duration (850/1450 ms), and the target location (left/right sides) were all randomized. Catch trials were employed in 20% of trials. In the initial fixation experiment, only two conditions were randomly mixed on each trial: (1) dim-bright-dim overlap and

(2) dim–bright gap. The difference from experiment 1 was the duration of the initial (dim) fixation period. It was randomly chosen from either 100 or 1000 ms on each trial, instead of 850 or 1450 ms. We expected that the 1000 ms duration would activate the sustained component of attention and produce RT reduction. In the gap experiment, data were analyzed with respect to 4 bright durations, 3 gap duration periods, and 2 locations, with each repeated 12 times, making in all 384 trials ( $4 \times 2 \times 2 \times 2 \times 12$ ). In the initial fixation experiment, there were 2 conditions, 3 gap durations, 2 locations, and 2 dim durations (the duration of the initial fixation stimulus), with each repeated 12 times, making in all 480 trials ( $2 \times 3 \times 2 \times 2 \times 20$ ). The remaining procedures were identical to those in experiment 1.

#### 4.2 Results

In both sub-experiments, the average false-alarm rate was 2% and 4%, respectively. In the gap experiment, the ANOVA revealed no differences in RTs in location; therefore data were pooled. Significant factors from the ANOVA are shown in table 4. The results in figure 7a indicate the shortest RTs with the gap duration 250 ms ( $p < 0.001$ ) in almost all bright durations (17, 50, 100, and 400 ms). RTs in the bright duration of 17 ms and 50 ms tended to be shorter for three subjects (YT, KM, NM). These data demonstrate that there is an optimal gap duration around 250 ms from fixation termination, and this can be obtained with the transient (less than 100 ms) fixation change. In the initial fixation experiment, RTs were shorter in the gap conditions than in the overlap conditions ( $116 \pm 29$  ms,  $p < 0.001$ ) with the exception of subject NM (see figure 7b). Furthermore, RTs were shorter with the dim duration of 1000 ms (with the sustained component) compared with the dim duration of 100 ms (with the transient component) in both gap ( $p < 0.01$ ) and overlap ( $p < 0.01$ ) conditions.

**Table 4.** Summary of analyses of variance of experiment 3.

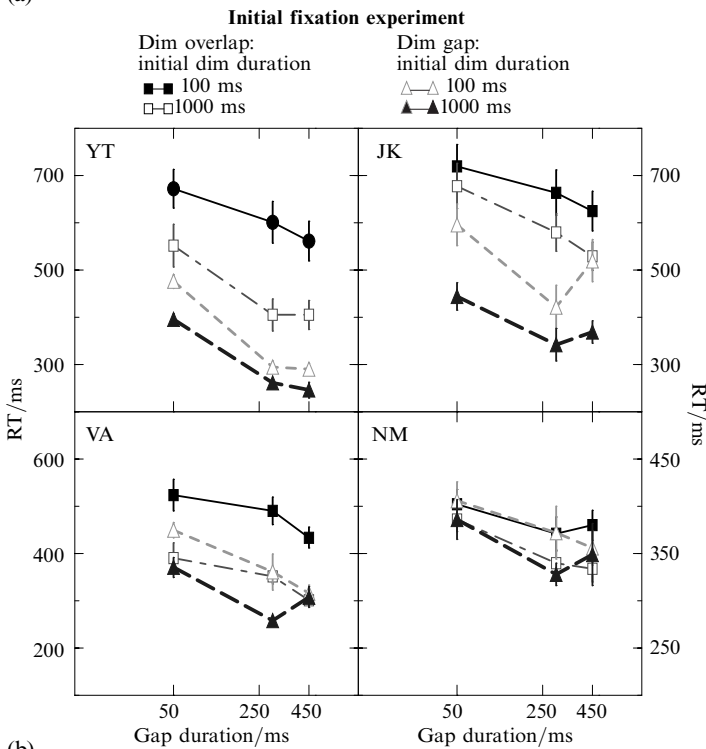
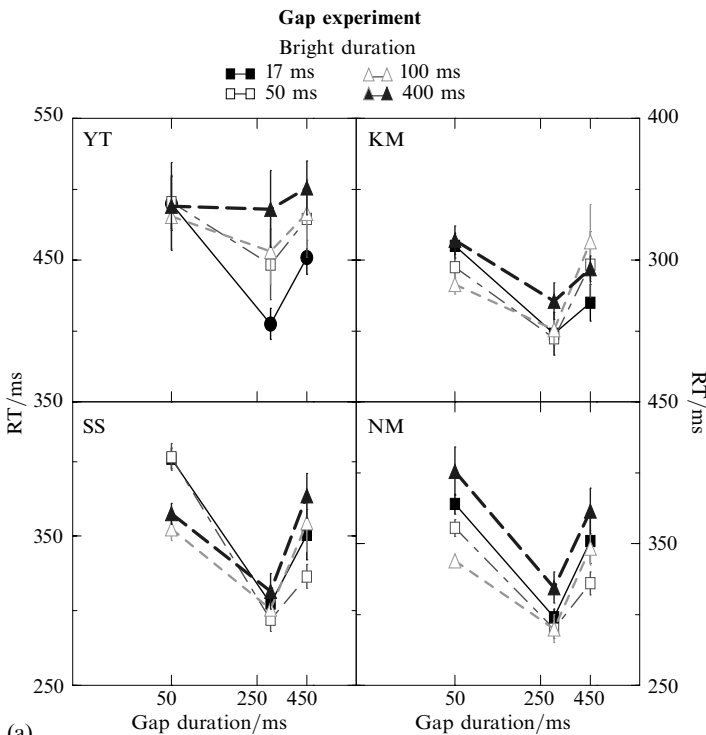
Task factor	<i>F</i>	<i>p</i>
Gap experiment		
bright duration	9.73	0.001**
gap duration	28.82	0.0001**
location $\times$ gap	4.04	0.01**
Initial fixation experiment		
dim duration	10.7	0.0001**
gap duration	14.6	0.0001**

Note: Data were analyzed with a three-way repeated-measures analysis of variance for each sub-experiment. Only the main effects and interactions that were significant are given.

\*  $p < 0.05$ , \*\*  $p < 0.01$

#### 4.3 Discussion

The results of the gap experiment demonstrate an optimal temporal parameter for the RT reduction. The optimal gap duration was 250 ms, the time course roughly comparable with that for express saccades (200 ms; Fischer and Boch 1983; Mayfrank et al 1986). The optimal duration of the fixation flash was less than 100 ms, confirming the involvement of the transient component of attention in the fast attention shifts (Shulman et al 1979; Nakayama and Mackeben 1989; Hikosaka et al 1993a). The results of the initial fixation experiment suggest that the sustained component before fixation termination is critical to the RT reduction, in accordance with the attentional engagement/disengagement hypothesis (Posner et al 1984; Fischer and Breitmeyer 1987; Mackeben and Nakayama 1993). These results suggest an interaction process between transient and sustained components of attention that produces fast disengagement and rapid shifts of attention.



**Figure 7.** Experiment 3. (a) Results of the gap experiment. Maximum RT reduction occurred with the gap duration 250 ms. (b) Results of the initial fixation experiment. RTs were shorter in the gap conditions than in the overlap conditions. Furthermore, RTs were further reduced when the initial dim fixation duration was long (1000 ms).

## 5 General discussion

We studied the characteristics of manual and saccade latencies manipulating spatial and temporal properties of the central fixation and peripheral visual stimuli. The results showed that a transient change at the fixation spot before its termination facilitated manual and saccadic responses to the peripheral targets in the gap paradigm.

### 5.1 *Involvement of attention*

The facilitation could be attributed to the general warning or timing effects elicited by the fixation change (Ross and Ross 1981; Reuter-Lorenz et al 1991, 1995). However, we think this unlikely for the following reasons. First, responses were facilitated only when a target location was pre-cued, whereas genuine cueing of timing, using entire visual-field cues, did not enhance facilitation (figure 6). Second, responses were not facilitated in overlap conditions that contained the transient cues (ie the dim–bright–dim-overlap condition), although the time course was identical to ‘transient’ gap conditions such as the dim–bright-gap condition (figure 2). Finally, the facilitation in the ‘transient’ gap condition was maximal at the gap duration of 250 ms in both manual and eye-movement tasks. This does not tie up with gap durations reported in the literature, where the maximal warning effect was reported to occur with gap durations of 100–200 ms for saccades (Ross and Ross 1981) and 300–500 ms for manual detection (Posner and Boies 1971; Tanaka and Sagi 2000). Instead, we consider an involvement of spatial attention as a possible mechanism underlying the effects. The first reason for this argument is that the facilitation was linked with the spatial orienting mechanism. Pre-cued locations produced enhanced facilitation in gap conditions, especially with transient signals (experiment 2). The second reason is that the facilitation was associated with visual stimuli (fixation mark) that contained a specific timing sequence (initial maintenance of fixation, its transient change, and disappearance) at the specific location (fixation spot). This spatial and temporal specificity suggests a particular mechanism instead of general timing hypotheses. The third reason is the common nature of performance (facilitation) between manual and eye-movement responses in the gap task (Fischer and Rogal 1986; Kingstone and Klein 1993; Tam and Stelmach 1993). One model that could explain our results would be as follows. First, attention is engaged at the central fixation mark during the initial fixation period. Then, it is automatically or involuntarily released when the fixation mark is removed and oriented to the pre-cued locus. Transient attention facilitates the disengagement and successive spatial orienting processes. This model is consistent with the attention disengagement hypothesis (Mayfrank et al 1986; Fischer and Breitmeyer 1987; Braun and Breitmeyer 1990; Mackeben and Nakayama 1993). Our results emphasize the exogenous nature of facilitation elicited by central transient cues during the disengagement process. This was linked to the spatial orienting mechanism.

### 5.2 *Interaction of two attention components*

For the maximum facilitation to take place in our experiments, it was critical for the sustained component of attention to be engaged at the fixation spot during the initial fixation period, followed by the activation of the transient component of attention before the fixation termination (gap). This suggests an interaction between the sustained and transient components of attention (Nakayama and Mackeben 1989). Here, we propose that the engagement process is tightly linked with slow and sustained attention (Hikosaka et al 1993b) which is modulated by the succeeding transient component during the disengagement process. This makes sense if we consider that the attentional engagement during the fixation may take time because of its voluntary and top–down nature (Fischer and Breitmeyer 1987; Hikosaka et al 1993b). Indeed, studies of ‘voluntary’ saccades such as antisaccade tasks show the modulation of sustained attention to the generation of eye movements (Fischer and Weber 1996; Abrams et al 1998) that is consistent with this

account. The results of spatial pre-cue experiments indicate that the activities of transient attention are associated with the exogenous orienting system. If we assume that this exogenous operation is linked with the overt orienting process that initiates saccades, the hypothesis is compatible with the recent studies of Fischer, Weber, and their colleagues (Weber and Fischer 1995; Fischer and Weber 1996, 1998; Weber et al 1998). Using a spatial (exogenous) cueing paradigm in the gap and overlap tasks (Cavan 1996), they directly tested the involvement of spatial attention while employing the pro-saccade and anti-saccade tasks whereby exogenous (bottom – up) or endogenous (top – down) attention was directed to the same or opposite side. Their data show that ‘transient’ (cue-lead time = 100 ms) pro-cues (shown to the attended side) facilitated generation of express saccades (figure 4), whereas anti-cues (opposite side) decreased express saccades (Fischer and Weber 1998). A significant number of error saccades was observed during antisaccades with pro-cues (Weber et al 1998). These results indicate that transient attention with valid cues can facilitate express saccades whereas sustained attention can inhibit them, demonstrating an interaction between transient and sustained attention in the generation of express saccades. The interaction between two attention components is consistent with our hypothesis in general, although in our current experiments sustained attention, which preceded transient attention, benefited facilitation instead of inhibition. In a different line of studies, we found that a spatial orienting mechanism employing detection, location discrimination, or saccadic eye-movement tasks (Posner and Cohen 1984; Rafal et al 1989) can be dissociated from an object recognition mechanism employing discrimination tasks of color, orientation, shape, etc (Tanaka and Shimojo 1996). The orienting mechanism was found to be operated in a transient manner, producing rapid attention shifts, whereas object recognition was found to be operated in a sustained and cumulative manner, generating visual short-term memory (Tanaka and Shimojo 2000). If it is assumed that object recognition processes require active focal attention, these results are in accordance with the idea of distinction/interaction between a fast and transient orienting mechanism and a slow and sustained recognition mechanism, although with a different time course (300–1000 ms for the transient mechanism and 1–20 s for the sustained mechanism, respectively). It is much less known, however, how these two systems interact.

### 5.3 *Relation to other studies*

Here, we review other relevant studies in the literature and discuss how they relate to our results. Tam and Stelmach (1993) examined the role of the ocular and attentional mechanisms in determining saccadic latencies by comparing manual responses and saccadic eye movements. They found that (i) turning off foveal or eccentric stimuli which were attended resulted in shorter saccadic latencies; (ii) saving of the latencies was greater with foveal than with eccentric attention; and (iii) express saccades were more prominent with foveal offsets. These are consistent with our results on the attentional involvement. Kingstone and Klein (1993) measured saccadic latencies, manipulating covert attention either endogenously and exogenously by using central arrows or eccentric flash of dots, respectively, while maintaining or extinguishing the central fixation stimuli (dots or arrows). On comparing manual and saccadic responses, they found two components of facilitation: one was attributed to the response preparation (warning) process, and the other was attributed to the oculomotor process induced by fixation offset (Munoz and Wurtz 1993a, 1993b). Our results showing facilitation with transient fixation change in the gap task (experiment 1) seem consistent with this model, although ‘warning effects’ by the transient signals in our study were found to be related to spatial attention (experiment 2). In the second experiment of Kingstone and Klein (1993), there was saccadic facilitation in the gap condition compared with the overlap condition when the central fixation mark was brightened shortly (96 ms) before its

termination. This is consistent with our results on eye movements (experiment 1). Second, greater facilitation (+19 ms) was shown with central brightening than with peripheral brightening in the gap condition in the same experiment. This is consistent with our attention hypothesis, if it is assumed that sustained attention is stronger in the fovea than in the periphery (Tam and Stelmach 1993). Cavan (1996) using the spatial precueing paradigm (Posner 1980) found that modulation of covert orienting generates fast saccades. An increased frequency of express saccades was found together with an accompanying decrease in their latencies by valid peripheral cues. This is consistent with our results in experiment 2 that showed the involvement of the spatial orienting mechanism (see also Crawford and Muller 1992). Recently, Kustov and Robinson (1996) found that the speed and direction of spatial orienting was modulated by microstimulation in the superior colliculus of monkeys, demonstrating a direct link between attention and saccadic eye movements. This may be a possible neuronal mechanism common to attention and oculomotor programming, although other studies emphasize contributions of parietal cortex (Colby et al 1996; Robinson et al 1996). It is not clear whether some interaction between the superior colliculus and the parietal cortex is critical in the generation of saccades (Rizzolatti et al 1987; Rafal et al 1989; Fischer and Weber 1993).

#### 5.4 Conclusion

In this study, we investigated temporal and spatial characteristics of attention. We found that the transient component of attention at the fixation spot before its termination facilitated manual and saccadic latencies of the peripheral target detection, possibly via attentional disengagement. The facilitation was tightly linked with the spatial orienting mechanism. For the maximal facilitation to occur, the sustained component of attention was necessary during the initial fixation period, suggesting an interaction between transient and sustained attention.

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#### References

- Abrams R A, Oonk H M, Pratt J, 1998 "Fixation point offsets facilitate endogenous saccades" *Perception & Psychophysics* **60** 201–208
- Bashinski H S, Bacharach V R, 1980 "Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations" *Perception & Psychophysics* **28** 241–248
- Bergen J R, Julesz B, 1983 "Parallel versus serial processing in rapid pattern discrimination" *Nature* **303** 696–698
- Braun D, Breitmeyer B G, 1990 "Effects of reappearance of fixed and attended stimuli upon saccadic reaction time" *Experimental Brain Research* **81** 318–324
- Breitmeyer B G, Ganz L, 1976 "Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing" *Psychological Review* **83** 1–36
- Cavan D, 1996 "Bilateral interactions in saccade programming. A saccade-latency study" *Experimental Brain Research* **109** 312–332
- Colby C L, Duhamel J R, Goldberg M E, 1996 "Visual, presaccadic, and cognitive activation of single neurons in monkey lateral intraparietal area" *Journal of Neurophysiology* **76** 2841–2852
- Crawford T J, Muller H J, 1992 "Spatial and temporal effects of spatial attention on human saccadic eye movements" *Vision Research* **32** 293–304
- Eriksen C W, Hoffman J E, 1972 "Some characteristics of selective attention in visual perception determined by vocal reaction time" *Perception & Psychophysics* **11** 169–171
- Fischer B, Boch B, 1983 "Saccadic eye movements after extremely short reaction times in the monkey" *Brain Research* **260** 21–26

- Fischer B, Breitmeyer B, 1987 "Mechanisms of visual attention revealed by saccadic eye movements" *Neuropsychologia* **25** 78–83
- Fischer B, Ramsperger E, 1984 "Human express saccades: extremely short reaction times of goal directed eye movements" *Experimental Brain Research* **57** 191–195
- Fischer B, Ramsperger E, 1986 "Human express saccades: effects of daily practice and randomization" *Experimental Brain Research* **64** 569–578
- Fischer B, Rogal L, 1986 "Eye-head coordination in man: A reaction time study" *Biological Cybernetics* **55** 253–261
- Fischer B, Weber H, 1993 "Express saccades and visual attention" *Behavioral Brain Research* **16** 533–610
- Fischer B, Weber H, 1996 "Effects of pre-cues on error rate and reaction times of antisaccades in human subjects" *Experimental Brain Research* **109** 507–512
- Fischer B, Weber H, 1998 "Effects of pre-cues on voluntary and reflexive saccade generation. I. Anti-cues for pro-saccades" *Experimental Brain Research* **120** 403–416
- Helmholtz H von, 1867/1962 *Treatise on Physiological Optics* volume 3 (New York: Dover, 1962); English translation by J P C Southall for the Optical Society of America (1925) from the 3rd German edition of *Handbuch der physiologischen Optik* (first published in 1867, Leipzig: Voss)
- Hikosaka O, Miyauchi S, Shimojo S, 1993a "Focal visual attention produces illusory temporal order and motion sensation" *Vision Research* **33** 1219–1240
- Hikosaka O, Miyauchi S, Shimojo S, 1993b "Voluntary and stimulus-induced attention detected as motion sensation" *Perception* **22** 517–526
- Jüttner M, Wolf W, 1992 "Occurrence of human express saccades depends on stimulus uncertainty" *Experimental Brain Research* **89** 678–681
- Kingstone A, Klein R, 1993 "Visual offsets facilitate saccadic latency: does predisengagement of visuospatial attention mediate this gap effect?" *Journal of Experimental Psychology: Human Perception and Performance* **19** 1251–1265
- Kustov A A, Robinson D L, 1996 "Shared neural control of attentional shifts and eye movements" *Nature* **384** 74–77
- Mackeben M, Nakayama K, 1993 "Express attentional shifts" *Vision Research* **33** 85–90
- Mayfrank L, Mobashery M, Kimming H, Fischer B, 1986 "The role of fixation and visual attention in the occurrence of express saccades in man" *European Archives of Psychiatry and Neural Science* **235** 269–275
- Müller H J, Rabbitt P M A, 1989 "Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption" *Journal of Experimental Psychology: Human Perception and Performance* **15** 315–330
- Munoz D P, Wurtz R H, 1993a "Fixation cells in monkey superior colliculus I. Characteristics of cell discharge" *Journal of Neurophysiology* **70** 559–575
- Munoz D P, Wurtz R H, 1993b "Fixation cells in monkey superior colliculus II. Reversible activation and deactivation" *Journal of Neurophysiology* **70** 576–589
- Nakayama K, Mackeben M, 1989 "Sustained and transient components of focal visual attention" *Vision Research* **29** 1631–1647
- Posner M I, 1974 "Psychobiology of attention", in *Handbook of Psychobiology* Eds C Blakemore, M S Gazzaniga (San Diego, CA: Academic Press)
- Posner M I, 1978 *Chronometric Explanations of Mind* (Hillsdale, NJ: Lawrence Erlbaum Associates)
- Posner M I, 1980 "Orienting of attention" *Quarterly Journal of Experimental Psychology* **32** 3–25
- Posner M I, Boies S J, 1971 "Components of attention" *Psychological Review* **78** 391–408
- Posner M I, Cohen Y, 1984 "Components of visual orienting" *Attention and Performance* **10** 531–556
- Posner M I, Cohen Y, Walker J A, Friedrich F J, Rafal R D, 1984 "Effects of parietal injury on covert orienting of attention" *Journal of Neuroscience* **4** 1863–1874
- Posner M I, Snyder C R R, Davidson B J, 1980 "Attention and detection of signals" *Journal of Experimental Psychology: General* **109** 160–174
- Rafal R D, Calabresi P A, Scioltio T K, 1989 "Saccade preparation inhibits reorienting to recently attended locations" *Journal of Experimental Psychology: Human Perception and Performance* **15** 673–685
- Remington R W, 1980 "Attention and saccadic eye movements" *Journal of Experimental Psychology: Human Perception and Performance* **6** 726–744
- Remington R W, Johnston J C, Yantis S, 1992 "Involuntary attentional capture by abrupt onsets" *Perception & Psychophysics* **51** 279–290

- Reuter-Lorenz P A, Hughes H C, Frensdreich R, 1991 "The reduction of saccadic latency by prior offset of the fixation point: an analysis of the 'gap' effect" *Perception & Psychophysics* **49** 167–175
- Reuter-Lorenz P A, Oonk H M, Hughes H C, 1995 "Effects of learning signals and fixation point offsets on the latencies of pro- versus antisaccades: implications for an interpretation of gap effect" *Experimental Brain Research* **103** 287–293
- Rizzolatti G, Riggio L, Dascola I, Umiltà C, 1987 "Reorienting attention across the horizontal and vertical meridians: Evidence in favor of premotor theory of attention" *Neuropsychologia* **25** 31–40
- Robinson D L, Bowman E M, Katzman C, 1996 "Covert orienting of attention in macaques. II. Contributions of parietal cortex" *Journal of Neurophysiology* **74** 698–712
- Ross L E, Ross S M, 1981 "Saccade latency and warning signals: effects of auditory and visual stimulus onset and offset" *Perception & Psychophysics* **29** 429–437
- Sagi D, Julesz B, 1984 "Detection versus discrimination of visual orientation" *Perception* **13** 619–628
- Sagi D, Julesz B, 1985 "'Where' and 'what' in vision" *Science* **228** 1217–1219
- Saslow M G, 1967 "Effects of components of displacement-step stimuli upon latency for saccadic eye movement" *Journal of the Optical Society of America* **57** 1024–1029
- Shimojo S, Tanaka Y, 1994 "'Super express' attentional shift" *Investigative Ophthalmology & Visual Science* **35**(4) 2147
- Shulman G I, Remington R W, McLean J P, 1979 "Moving attention through visual space" *Journal of Experimental Psychology: Human Perception & Performance* **5** 522–526
- Tam W A J, Stelmach L B, 1993 "Viewing behavior: Ocular and attentional disengagement" *Perception & Psychophysics* **54** 211–222
- Tanaka Y, Sagi D, 2000 "Attention and short-term memory in contrast detection" *Vision Research* **40** 1089–1100
- Tanaka Y, Shimojo S, 1996 "Location versus feature: Reaction time reveals dissociation between two visual functions" *Vision Research* **36** 2125–2140
- Tanaka Y, Shimojo S, 2000 "Repetition priming reveals sustained facilitation and transient inhibition in reaction time" *Journal of Experimental Psychology: Human Perception and Performance* **26** 1421–1435
- Wagner G, Boynton R M, 1972 "Comparison for four methods of heterochromatic photometry" *Journal of the Optical Society of America* **62** 1508–1515
- Weber H, Durr N, Fischer B, 1998 "Effects of pre-cues on voluntary and reflexive saccade generation. II. Pre-cues for anti-saccades" *Experimental Brain Research* **120** 417–431
- Weber H, Fischer B, 1995 "Gap duration and location of attention focus modulate the occurrence of left/right asymmetries in the saccadic reaction times of human subjects" *Vision Research* **35** 987–998