



## The time course of top-down control on saccade averaging



J. Heeman<sup>a,\*</sup>, J. Theeuwes<sup>b</sup>, S. Van der Stigchel<sup>a</sup>

<sup>a</sup> Experimental Psychology, Helmholtz Institute, Utrecht University, Utrecht, The Netherlands

<sup>b</sup> Department of Cognitive Psychology, Vrije Universiteit, Amsterdam, The Netherlands

### ARTICLE INFO

#### Article history:

Received 8 November 2013

Received in revised form 20 February 2014

Available online 13 April 2014

#### Keywords:

Global effect  
Saccade averaging  
Top-down control  
Time course  
Task demand  
Inter-trial priming

### ABSTRACT

When objects in a visual scene are positioned in close proximity, eye movements to these objects tend to land at an intermediate location between the objects (i.e. the global effect). This effect is most pronounced for short latency saccades and is therefore believed to be reflexive and dominantly controlled by bottom-up information. At longer latencies this effect can be modulated by top-down factors. The current study established the time course at which top-down information starts to have an influence on bottom-up averaging. In a standard global effect task two peripheral stimuli (a red and a green abrupt onset) were positioned within an angular distance of 20°. In the condition in which observers received no specific target instruction, the eyes landed in between the red and green element establishing the classic global effect. However, when observers were instructed to make a saccade to the red element during a whole block or when the target color varied from trial-to-trial (red or green), a clear effect of the target instruction on the accuracy of the landing position of the primary saccade was found. With increasing saccade latencies, the eyes landed closer to the instructed target. Crucially, however, this effect was even seen for the shortest saccade latencies (as early as 200 ms), suggesting that saccade averaging is affected early on by top-down processes.

© 2014 Elsevier Ltd. All rights reserved.

### 1. Introduction

When two adjoining stimuli in the same hemifield evoke a short-latency saccade, the saccade tends to land on an intermediate location between these stimuli (Coren & Hoenig, 1972). This effect is known as the *global effect* or *saccade averaging* and occurs when stimuli are presented relatively close to each other (less than 35° angular distance) (Findlay, 1982; Van der Stigchel, Heeman, & Nijboer, 2012; Van der Stigchel & Nijboer, 2011, 2013; Walker et al., 1997). The global effect has originally been explained by a weighted average account. According to this view, all elements in a visual scene evoke a peak of activity in a common saccade map. When the elements are positioned close together these peaks of activity overlap and merge resulting in one vector determining the direction and the landing position of the saccade (Tipper, Howard, & Jackson, 1997). This model assumes that target selection is the result of competitive interaction between groups of neurons that code for the possible targets locations in a common saccade map. In recent years the weighted average account has been extended from a mechanism driven by bottom-up processes only

to models that also integrates higher-order information (Fecteau & Munoz, 2006; Findlay & Walker, 1999; Godijn & Theeuwes, 2002; McSorley, Haggard, & Walker, 2006; Meeter, Van der Stigchel, & Theeuwes, 2010; Trappenberg et al., 2001). In these models the activity of each subset of neurons is the result of the integration of low-level visual information and higher-order information. When, based on higher-order information, one of the elements is designated as the target the activity associated with the target location will be enhanced relative to the activity associated with the distractor. If the peaks of activity of target and distractor overlap, the enhancement of activity of the target will result in a saccade endpoint which is shifted towards the target.

Latency has a strong influence on the size of the global effect. In general, saccade averaging is more pronounced for short latency saccades (Edelman & Keller, 1998; Findlay, 1982). Ottes, Van Gisbergen, and Eggermont (1985) showed in experiments in which participants were instructed to make a saccade to a target in the presence of non-targets that saccades landed more accurately on the target when saccade latencies were longer. The global effect completely disappeared when the time between target onset and saccade initiation was longer than 300 ms. In studies with monkeys it has been shown that the likelihood of saccades being averaged was larger for express saccades (with a latency of less than 100 ms) than for slower saccades (Chou, 1999). The early

\* Corresponding author. Address: Experimental Psychology, Helmholtz Institute, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands. Fax: +31 30 253 4511.

E-mail address: [j.heeman@uu.nl](mailto:j.heeman@uu.nl) (J. Heeman).

global effect studies that labeled one of the elements as a target and the other as a distractor found that a task instruction did not reduce the global effect, supporting the claim that the global effect is automatic and cannot be influenced by higher-order signals (Menz & Groner, 1987; Ottes, Van Gisbergen, & Eggermont, 1985). Because of this apparent time course, in which there is a global effect for short latency saccades and no global effect for long latency saccades, the global effect is often considered reflexive and driven by bottom-up processes.

In subsequent years, however, more and more evidence accumulated suggesting that various processes that are considered top-down in origin do influence the saccade landing position. The first researchers to rebut the purely reflexive nature of the global effect mechanism were Coëffé and O'Regan (1987). Their study presented participants a string of letters that contained a target letter marked with an 'x' to which they had to make a fast saccade. In one of their conditions the location of the 'x' remained constant during the entire experimental block. They showed that, even for short latency saccades, this predictability of the location of the target letter decreased the size of the global effect. Eye movements were initiated more accurately towards the target location than in the conditions in which the location of the 'x' was varied. Other evidence that shows that the size of the global effect can be modulated or even abolished by top-down processes came from studies which varied the probability of the target location (He & Kowler, 1989), gave an auditory cue before each trial which provided information about the location of the target (Aitsebaomo & Bedell, 2000), or gave participants the opportunity to pre-examine the possible targets in a scene before getting the final task instruction (Findlay & Blythe, 2009). All of these studies show that additional higher-order information about the target increases saccade accuracy to the target and decreases the global effect (for a review, see Van der Stigchel & Nijboer, 2011).

Although it is known that saccade averaging is stronger for short latency saccades, the time course of the modulating influence of top-down processes is unknown. It is currently unclear whether there is a gradual built up of top-down influence or whether the time course is more in line with a race-model that follows the winner-takes-all principle. In relation to visual search, Van Zoest, Donk, and Theeuwes (2004) showed that the exogenous process of bottom-up stimulus-driven target selection and the endogenous process of top-down goal-driven selection operate on independent time scales. They suggested that longer latency responses will become increasingly goal-driven at the expense of the bottom-up stimulus-driven response. The present study seeks out to further investigate this assumption by establishing a detailed time course of the interaction between top-down and bottom-up influence on saccades in relation to the global effect. It will therefore be established for which latencies the bottom-up saccade averaging is influenced by top-down task instruction.

To investigate the time course of the modulating influence of top-down processes on the global effect a task was designed in which participants were required to saccade to one of two elements in near periphery with a wide range of saccade latencies. To evoke a wide range of saccade latencies a fixation gap paradigm was used varying the fixation offset and stimulus onset timing between overlap, no-gap or gap trials. The shorter the overlap (or the longer the gap) between fixation offset and stimulus onset the shorter the latency of the saccade (Kopocz, 1995; Saslow, 1967).

## 2. Experiment 1

The first experiment investigated to what extent the ability of participants to saccade to a specific target element depended on

the latency of the saccade. Experiment 1 contained three conditions. An Instruction condition in which the color of the element to which the saccade had to be made was specified and the other element served as a distractor (Double Instruction) and two No Instruction conditions that served as a baseline for the analysis, one in which two elements were presented without a target color instruction (Double No Instruction) and one condition in which only a single element was presented (Single).

### 2.1. Methods

#### 2.1.1. Participants

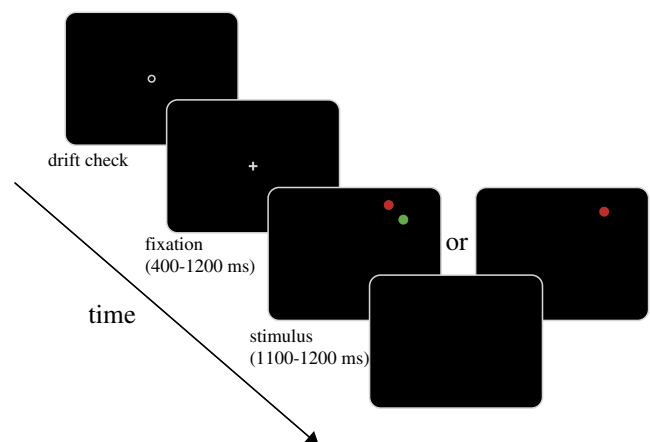
Ten naive participants (22–40 years old/average age 31.5 years; 4 male), all naive to the purpose of the experiment, participated in the experiment. All had normal or corrected-to-normal visual acuity. Informed consent was obtained prior to the study in accordance with the guidelines of the Helsinki Declaration.

#### 2.1.2. Apparatus

Participants performed the experiment in a sound-attenuated setting, viewing a display monitor from a distance of 72 cm. Eye movements were recorded by an Eyelink1000 system (desktop system; SR Research Ltd., Canada), an infra-red video-based eye tracker that has a 1000 Hz temporal resolution and a spatial resolution of 0.01°. The participant's head was stabilized with a chin rest, and an infrared remote tracking system compensated for any residual head motion. The left eye was monitored. An eye movement was considered a saccade when either eye velocity exceeded 35°/s or eye acceleration exceeded 9500°/s<sup>2</sup>.

#### 2.1.3. Stimuli and procedure

Participants viewed a display containing a gray cross (1° × 1°, 13.3 cd/m<sup>2</sup>) on a black background in the center of the display, which was used as fixation point. The fixation point was removed after a random interval of 400–1200 ms. Stimulus onset was either 50 ms or 100 ms before fixation offset (overlap), simultaneous with fixation offset (no gap), or 50 ms or 100 ms after fixation offset (gap). Gap, no gap and overlap trials were counterbalanced and intermixed in a random fashion. The target display was presented for 1100–1200 ms. Afterwards all objects were removed from the display. The stimuli, a red and a green filled circle, had the same size (.75°) and were equiluminant (7.98 cd/m<sup>2</sup>). The distance from the central fixation point to the stimuli was 8°. Fig. 1 shows a schematic representation of the trial sequence of Experiment 1. Either one or two elements could be presented. When one element was



**Fig. 1.** Schematic representation of the task of Experiment 1 presenting either two peripheral elements or one. The stimulus onset asynchronies were –100, –50, 0, 50 and 50 ms relative to fixation offset.

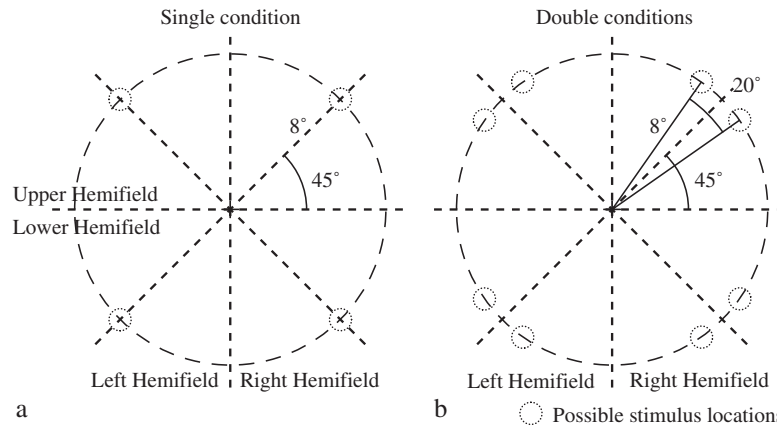


Fig. 2. Template of distances and possible stimulus locations in the condition presenting one element (a) and the conditions presenting two elements (b).

presented, the element appeared on one of the principal axes (45°, 135°, 225°, 315°) (see Fig. 2a). When two elements were positioned, they were displayed in the same quadrant and were positioned around four principal axes (45°, 135°, 225°, 315°). Each element appeared on either side of the axis at equal distance from the axis. The distance between the center of the circles was 20° (see Fig. 2b). In half the trials with two elements the red stimulus was presented on the left side of the axis and in the other half the trials with two elements the red stimulus was presented on the right side of the axis.

The experiment consisted of three blocks over two sessions. In the Double Instruction block, the task was to make an eye movement, as fast as possible, to the red target and ignore the green distractor. In the Double No Instruction block (also consisting of a red and a green circle), and the Single circle block (only a red circle), participants were instructed to move their eyes as fast as possible to the stimuli presented (i.e. no target was specified). Both blocks with two elements on the display consisted of 480 experimental trials and 40 practice trials. The block with only one element consisted of 120 experimental trials and 20 practice trials. The order of the blocks was counterbalanced.

Each session started with a nine-point grid calibration procedure. In addition, simultaneously fixating the central fixation point and pressing the space bar recalibrated the system by zeroing the offset of the measuring device at the start of each trial.

## 2.2. Data analysis

### 2.2.1. Preprocessing

The saccade landing position was calculated as a proportion of the angle between the red and the green stimulus locations of the Double conditions. The geometric midpoint between the two stimuli represented the line of *perfect averaging* between the two elements and served as the null-reference for of the landing position ( $\varphi = 0.0$ ). Saccades which landed towards the red element were defined as having a negative landing position and saccades that landed towards the green element were defined as having a positive landing position. Saccades which landed on the red element had a landing position of minus one ( $\varphi = -1.0$ ) and saccades which landed on the green element had a landing position of one ( $\varphi = 1.0$ ). This also means that in the condition that involved the task instruction ('make an eye movement to the red element') saccades with a landing position of  $\varphi = -1.0$  landed on the target. The landing position in the condition with one element was obtained in the same way using the stimulus locations conditions with two elements as a frame of reference. Because, however, the single element was positioned on the axis a landing position of

zero ( $\varphi = 0.0$ ) means that the saccade landed on the element. To compensate for small drift ( $\leq 1^\circ$ ) of the eye movements from fixation at the start of the saccade, the actual starting point of the saccade was used to calculate the landing position ( $\varphi$ ). A schematic representation of how the landing position was quantified is shown in Fig. 3. Saccades which landed more than two and a half standard deviations from the participants mean were regarded as outliers and removed from the analysis.

Saccade latency was defined as the interval between the stimulus onset and the moment of initiation of the first saccadic eye movement. Trials were filtered on saccade latency with a minimum latency of 80 ms (anticipatory saccades) and a maximum latency of more than two and a half standard deviations away from the mean latency. Trials with a saccadic latency outside these bounds were excluded.

### 2.2.2. Statistical analysis

To investigate to what extent the influence of the task instruction on saccade landing position was modulated by saccade latency, the trials of each participant were sorted from short saccade latency to long latency saccades and divided into 5 bins, each bin containing 1/5th of the trials. For each quintile the mean landing position with respect to the line of *perfect averaging* was calculated and analyzed by running an analysis of variance (ANOVA) with Condition (Single, Double No Instruction, Double Instruction) and Latency Bin (Bin 1: short latency through Bin 5: long latency) as factors. If the bins differed, planned comparisons were used to determine whether the landing position showed a

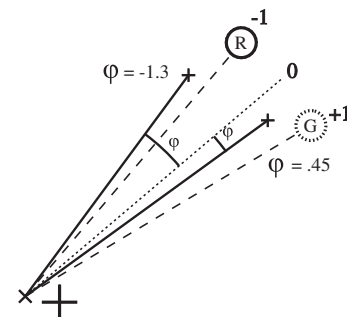


Fig. 3. Schematic representation of the saccade landing position measure that is used in Experiment 1 and 2. The saccade landing position was calculated as a proportion of the angle between the red (R) and the green (G) stimulus locations of the Double conditions. The geometric midpoint between the two stimuli represented the line of *perfect averaging* and served as the null-reference for of the landing position ( $\varphi = 0.0$ ). Two example landing positions (+) are shown.

linear contrast for the shift of the landing position towards the target as a function of the increase in latency. To establish if there were differences in landing position for the shortest latency saccades, the fastest saccades, contained in the first bin, were analyzed using an ANOVA with Condition (Single, Double No Instruction, Double Instruction) as a factor.

The median latencies of the Single, Double No Instruction and Double Instruction conditions were analyzed to test if the latencies varied between conditions. This analysis was performed through an ANOVA with Condition as a factor.

### 2.3. Results Experiment 1

#### 2.3.1. Exclusions

The exclusion criteria led to a loss of 7.08% of the trials.

#### 2.3.2. Landing position

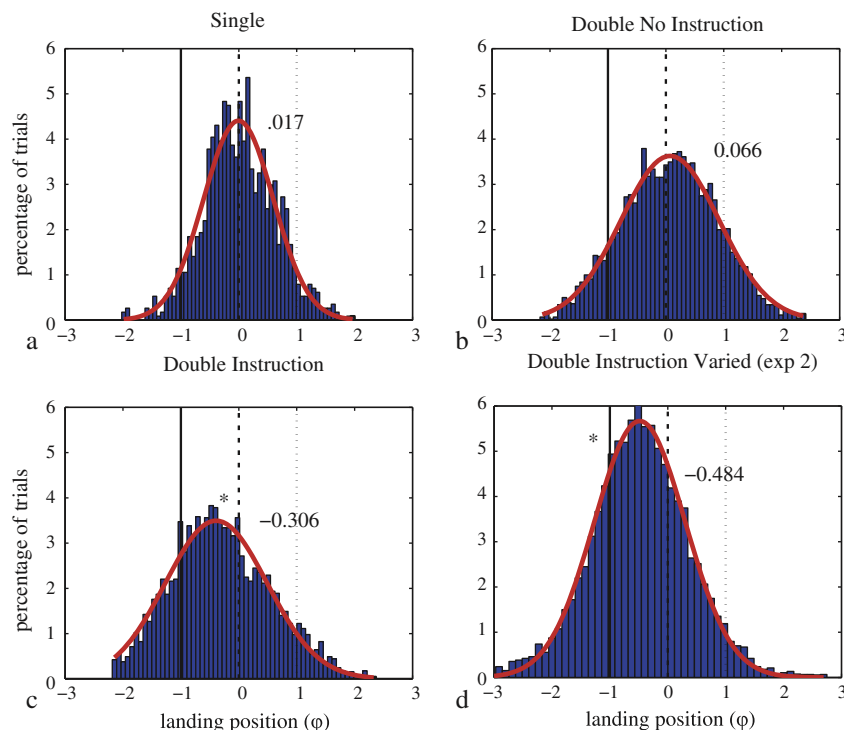
A main effect of Condition ( $F(2,18) = 26.863$ ,  $p < .001$ ) was found. Saccade landing position in the conditions without a task instruction (Single and Double No Instruction) landed close to the line of *perfect averaging* (Single: mean = .017, sd = .054; Double No Instruction: mean = .066, sd = .068). As expected, the peak of the landing position in the Single condition was nicely on the target ( $\varphi = 0$ ), this is confirmed by a post hoc  $t$ -test (Single vs. target location:  $t(9) = .974$ ,  $p = .355$ ). It can also be seen that in the Double No Instruction condition the stimuli evoked a strong global effect, saccades landed at or near the line of *perfect averaging*. Post hoc testing confirms that saccades in the Double condition behaved as if the target was positioned in the middle between the two stimuli (*perfect averaging*) at the same location as the target in the Single condition. The landing position in the Single and Double No Instruction conditions did not differ from each other (Single vs. Double:  $t(9) = 1.638$ ,  $p = .136$ ). Conversely, saccade

landing positions in the condition that involved a task instruction (Double Instruction) deviated towards the red element which served as a target in this condition (mean =  $-.306$ , sd = .21). The global effect is significantly weaker for the Double Instruction condition and the peak of the landing position in this condition has shifted towards the red target element (Double Instruction vs. *perfect averaging*:  $t(9) = 4.689$ ,  $p < .001$ ). Fig. 4 shows the frequency distribution for all three conditions, the number in each graph quantifies the location of the mean of the distribution. It can be seen that all three conditions evoke a unimodal peak of the saccadic landing position.

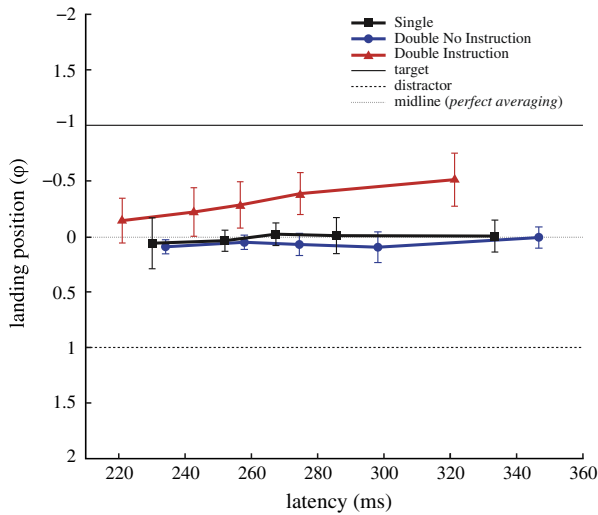
The interaction between Condition and Bin was significant ( $F(8,72) = 3.657$ ,  $p = .001$ ). As indicated by planned comparison linear contrasts, landing positions in the Single and Double No Instruction condition did not vary between bins whereas saccade landing positions in the Instruction condition deviated progressively more towards the red target element with increasing saccade latency (Single:  $F(1,9) = .629$ ,  $p = .448$ ; Double No Instruction:  $F(1,9) = 1.608$ ,  $p = .236$ ; Double Instruction:  $F(1,9) = 42.874$ ,  $p < .001$ ). Fig. 5 shows the landing position per bin as a function of the latency for all conditions.

For the fastest bins, there was a main effect of Condition ( $F(2,18) = 4.920$ ;  $p < .02$ ). Even for the fastest saccades, the landing position in the condition with the task instruction deviated significantly more towards the red target than landing positions in the Double No Instruction condition ( $t(9) = 3.245$ ,  $p = .010$ ).

To investigate whether our gap/overlap manipulation influenced the observed relationship between saccade averaging and saccade latency in the Double Instruction condition, we performed an ANOVA with Gap/Overlap duration and Bin as factors. No significant interaction was observed ( $F(16,144) = 1.086$ ,  $p = .373$ ), indicating that the reported relationship between averaging and saccade latency was completely independent from the gap/overlap duration (see also McSorley, Cruickshank, & Inman, 2009).



**Fig. 4.** A frequency plot for all conditions of Experiment 1 (a–c) and Experiment 2 (d). In the Single condition (a) the target element was presented at the location with value 0. The green element and the red element in the Double No Instruction and the Double Instruction conditions (b and c) were presented at the locations with value 1 for  $-1$  respectively. In the Double Instruction conditions (d) of Experiment 2  $-1$  was the location of the target and 1 was the location of the distractor. Asterisks indicate a significant deviation from *perfect averaging*. The mean value of saccade landing position in all conditions is given in each plot.



**Fig. 5.** Mean landing position of the primary saccade divided into 5 latency bins for all three conditions: to a single target without the presence of a distractor (■); to a double stimulus without a task instruction (●); to a double stimulus with the instruction to make a saccade to the red stimulus (▲). Error bars indicate the standard deviation.

2.3.3. Saccade latency

An ANOVA on the medians of the saccade latency with Condition (Single, Double No Instruction and Double Instruction) as a factor indicated that there was no significant effect of Condition ( $F(2, 18) = .600, p = .559$ ). All three conditions displayed a similar latency distribution (see Fig. 6).

2.4. Discussion Experiment 1

The results of Experiment 1 indicate that the size of the global effect is dependent on the time between stimulus onset and saccade initiation (e.g. saccade latency). The increase in accuracy has a relationship with saccade latency that is almost linear: short saccade latencies result in a stronger global effect, whereas longer latencies result in a gradual weakening of the global effect. It can be noted that even for the shortest saccades latencies higher-order information has an effect on saccade averaging. In terms of the weighted average account, these results indicate that when more time is available the weight of the target gradually becomes larger and the weight of the distractor becomes smaller under the influence of the processing of top-down information (also see Godijn & Theeuwes, 2002). This is reflected in a shift of the saccade landing position towards the target. These results are in line with the priority map model (Fecteau & Munoz, 2006) that allows for gradual top-down modulation of bottom-up oculomotor processes by

combining salience of an element and relevance of an element in a single map.

It is, however, also known that the response to a target in a single trial can be enhanced by presenting the same target over and over again in consecutive trials. It can, therefore, be argued that the shift in landing position towards the target in the Instruction condition does not reflect a top-down influence but is the result of an effect known as inter-trial priming (Theeuwes, 2013; Theeuwes, Reimann, & Mortier, 2006). The target is primed by previous trials and this effect is enhanced when more trials with the same target follow each other (Rastgardani et al., 2009; Theeuwes, 2010). For instance, several studies have shown that response times in visual search tasks become shorter if the target features remain the same across trials. This improvement is not the result of top-down knowledge about the target but of an automatic bottom-up feature driven priming effect of the same target presented in consecutive trials. The same mechanism that is responsible for improving performance in visual search could be responsible for an enhanced weight of an element in a saccade averaging task like Experiment 1. In the Instruction condition the red element was the target throughout all trials. The target color did not vary from trial-to-trial. This constant instruction could have resulted in an increased weight of the red target. The shift of the saccadic landing position towards the red target can, therefore, easily be attributed to inter-trial priming instead of the being result of top-down modulation by the task instruction.

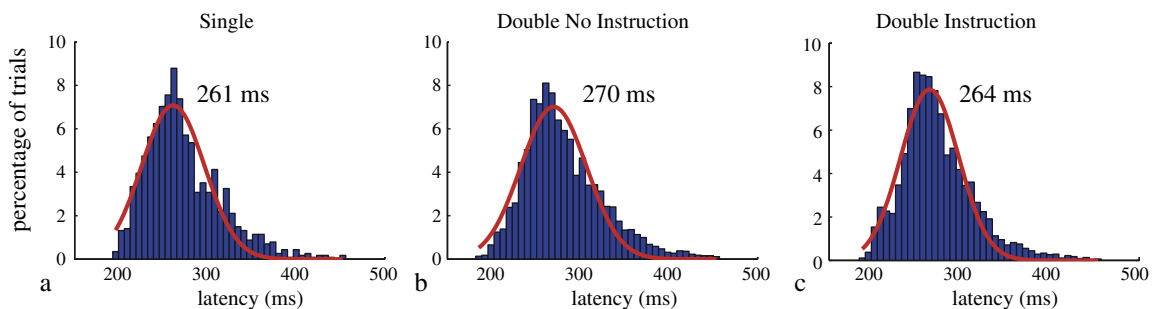
To investigate this possibility the paradigm of Experiment 1 was extended to a paradigm that varied the task instruction randomly from trial-to-trial. In Experiment 2, again, the ability of participants to accurately saccade to a target was tested, however, the instruction which of the two elements was the target varied from trial-to-trial. Each trial started with an instructional word ('red' or 'green') defining the color of the target element in that trial only. This revealed whether the ability to saccade to the target was influenced by priming effects evoked by preceding trials with the same task instruction. Furthermore, to examine the latency distribution in more detail, we increased the number of trials to 800 per condition to allow a division in 10 bins for Experiment 2 instead of 5 bins in Experiment 1 (with 480 trials).

3. Experiment 2

3.1. Methods

3.1.1. Participants

Fourteen participants (19–40 years old/average age 25.7 years; 4 male), naive to the purpose of the experiment, participated in the experiment. All had normal or corrected-to-normal visual acuity. Informed consent was obtained prior to the study in accordance with the guidelines of the Helsinki Declaration.



**Fig. 6.** Frequency distribution plot of saccade latency for the Single (a), Double No Instruction (b) and the Double Instruction condition (c). The mean value is given in each figure.

### 3.1.2. Apparatus

The same apparatus and experimental setup as in Experiment 1 was used.

### 3.1.3. Stimuli and procedure

Experiment 2 only included a Double Instruction condition. The procedure and stimuli were the same as in the Double Instruction condition of Experiment 1 with one exception: each trial started with the presentation of an instructional word ('rood' (red) or 'groen' (green)) in lowercase letters with a height of  $0.5^\circ$  at the same location as the fixation cross. This word cue indicated which color circle was to be the target of that trial and which color circle had to be ignored. Each of the two words was presented in half the trials (counterbalanced). The word was presented for 700 ms after which the word disappeared and the fixation cross appeared for 400–900 ms. The rest of the trial sequence was identical to the Double Instruction condition of Experiment 1. Fig. 7 shows a schematic representation of the trial sequence of Experiment 2.

Experiment 2 consisted of 32 training trials and 800 experimental trials per participant.

## 3.2. Data analysis

### 3.2.1. Preprocessing

The landing position ( $\varphi$ ) was calculated in the same way as in Experiment 1 with one exception. Since the task instruction varied from trial-to-trial, the *target element* (red or green) instead of the red element was defined as minus one. This meant collapsing the data in such a way that the target element, and not the red element, was always on the minus one location and the distractor at the one location (see Fig. 3).

The same exclusion criteria as in Experiment 1 were applied to the trials of Experiment 2.

### 3.2.2. Statistical analysis

To get an overall idea of saccadic behavior the saccade landing positions were first divided into 10 Latency Bins (Bin 1 (short latency) through 10 (long latency)) following the same procedure as in Experiment 1. It was tested with a *t*-test whether the first bin deviated from 0 (*perfect averaging*). If the first bin deviated from *perfect averaging*, a planned comparison was used to investigate whether the landing positions of bin 1 and through 10 showed

a linear contrast when relating the shift towards of the landing position to the increase in latency.

Next, the large number of trials in Experiment 2 enabled us to zoom in on the time course of sequences of consecutive trials with the same task instruction and analyze the data with respect to inter-trial priming. All trials were categorized based on the number of trials preceding that trial with the same task instruction. If, for example, at the beginning of a trial the red element was designated as the target color and for the preceding trial the color of the target element was also red it was considered a sequence of 2 red trials. If the two preceding trials had red as the task instruction it was considered a sequence of 3 trials, etc. Trials that were preceded by a trial with a different task instruction were defined as *switch trials*. Sequences of up to 11 trials randomly occurred during the experiment. Due to their rare occurrence trial sequences of 6 or longer were not included in the analysis. After categorizing the trials the saccade landing positions of each category was binned into Latency Bins according to the same binning procedure as explained in Experiment 1. To maintain statistical power the data was now divided into 5 bins instead of 10 bins. To investigate how the time course of saccade accuracy was affected by preceding trials, an ANOVA with Sequence length (switch trial up to sequence of 5 trials) and Latency Bin (Bin 1 (short latency) through 5 (long latency)) as factors was performed.

The median latencies of the five different sequence lengths were analyzed to test if the latencies varied between them. This analysis was performed through an ANOVA with Sequence length (switch trial up to sequence of 5 trials) as a factor.

## 3.3. Results and discussion Experiment 2

### 3.3.1. Exclusions

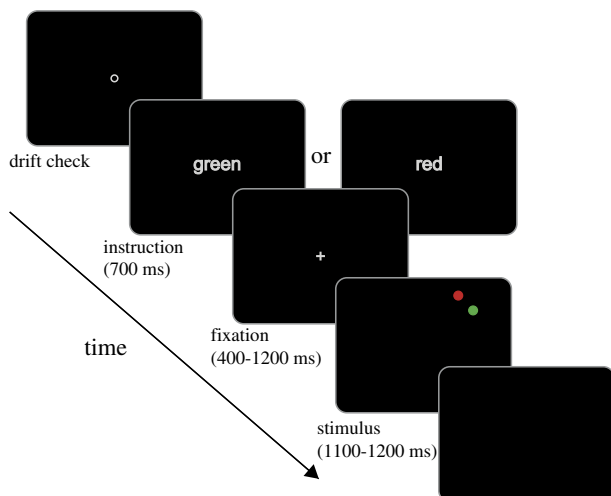
The exclusion criteria led to a loss of 7.04% of the trials.

### 3.3.2. Landing position

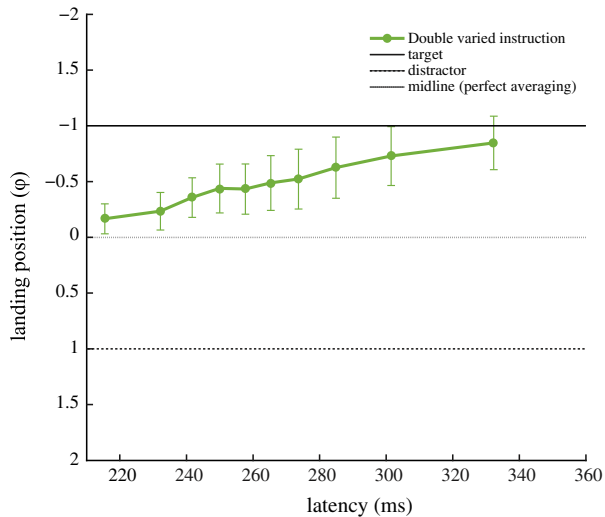
Like in Experiment 1, the distribution of the saccade landing position of all trials showed a unimodal distribution with a shift towards the target (mean =  $-.484$ ,  $sd = .059$ , see Fig. 4d).

The saccade landing positions were divided into 10 bins in the same way as has been done for Experiment 1. The data shows that the first bin has a significant deviation away from the midline between the two stimuli (*perfect averaging*) towards the target ( $t(13) = 4.627$ ,  $p < .001$ ). As in Experiment 1 the deviation of the binned landing positions of Experiment 2 follows an increasing linear trend towards the target from Bin 1 to Bin 10 ( $F(1,9) = 38.512$ ,  $p < .001$ ) (see Fig. 8).

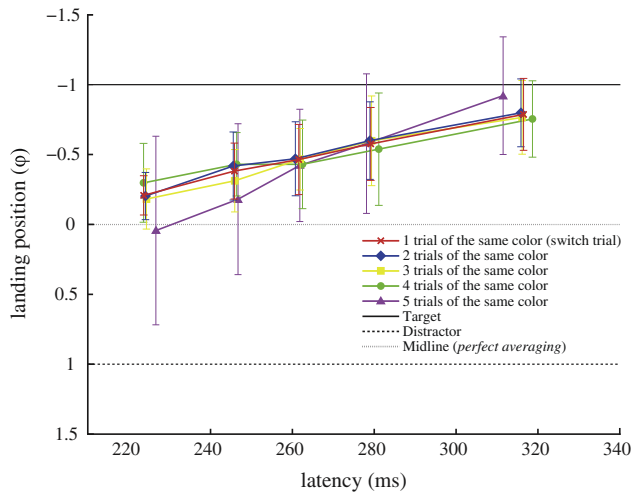
Next the time course of sequences of consecutive trials with the same task instruction was analyzed. Fig. 9 shows a plot of the landing position as a function of saccade latency per sequence length. Each line represents a specific number of consecutive trials with the same task instruction. To maintain statistical power the data was now divided into 5 bins instead of 10 bins. An ANOVA with Sequence length (switch trial up to sequence of 5 trials) and Latency Bin (Bin 1: short latency through Bin 5: long latency) as factors reveals that there was no effect of Sequence length ( $F(4,52) = .976$ ,  $p = .429$ ). This shows that the number of trials preceding a trial did not affect the landing position during a trial. There was an effect of Latency Bin ( $F(4,52) = 53.132$ ,  $p < .001$ ). Like in Experiment 1 the planned comparison revealed a linear contrast ( $F(1,13) = 113.68$ ,  $p < .001$ ). The deviation of the landing position away from *perfect averaging* and towards the target increased with increasing latency. There was no interaction between Sequence Length and Latency Bin ( $F(16,208) = 1.208$ ,  $p = .264$ ). The landing positions showed, regardless of sequence length, a comparable deviation of the landing position depending on the bin. Since we are especially interested in saccadic behavior for the shortest



**Fig. 7.** Schematic representation of the task of Experiment 2 presenting an instructional word followed by two peripheral elements. The stimulus onset asynchronies were  $-100$ ,  $-50$ ,  $0$ ,  $50$  and  $50$  ms relative to fixation offset.



**Fig. 8.** Mean landing position of the primary saccade divided into 10 latency bins for the condition with the variable task instruction. Error bars indicate the standard deviation.



**Fig. 9.** Mean landing position of the primary saccade to the two peripheral stimuli. Each line represents a specific number of consecutive trials in which the task instruction remained the same. Error bars indicate the standard deviation.

latency saccades we performed several post hoc tests on Bin 1 only. An ANOVA of Bin 1 of all Sequences (switch trial up to sequence of 5 trials) shows that there is no difference in landing position between the 5 sequence of consecutive instructions of Bin 1 ( $F(1,4) = 1,736, p = .156$ ). Performing a  $t$ -test of Bin 1 for each sequence of consecutive trials shows that only the longest sequence of trials (5 consecutive trials) no longer deviates towards the target. The results of the  $t$ -tests are shown in Table 1 and are corrected for multiple comparisons.

Again, no significant interaction between Gap/Overlap duration and Bin was observed ( $F(36,468) = 1.031, p = .423$ ), indicating that the reported relationship between averaging and saccade latency was completely independent from the gap/overlap duration.

Experiment 2 indicates there was no effect of inter-trial priming on the deviation of the saccade landing position. Had there been an effect of inter-trial priming the saccade landing position in switch trials would have shown a stronger global effect especially in the first short latency bins compared to the saccade landing position in longer sequences of same instruction trials. The number of preceding same instruction trials, however, did not affect the landing

**Table 1**

Results of  $t$ -test testing Bin 1 containing the shortest latency saccades against the midline between stimuli (*perfect averaging*). Results are corrected for multiple comparisons.

| Number of consecutive trials with the same instruction | $t(13)$ | $p$    |
|--|---------|--------|
| Switch trials  | 5.532   | <.001* |
| 1 preceding trial of the same color                    | 4.489   | .001*  |
| 2 preceding trials of the same color                   | 3.161   | .008*  |
| 3 preceding trials of the same color                   | 3.945   | .002*  |
| 4 preceding trials of the same color                   | .242    | .812   |

\*  $p < .01$ .

position. Therefore the possibility that the findings in Experiment 1 are mistaken for a bottom-up process due to inter-trial priming has been eliminated.

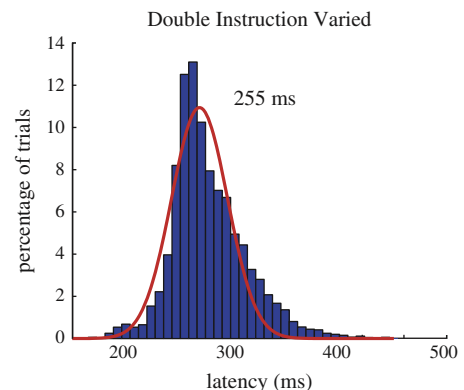
One might argue that the absence of a deviation towards the target in sequences of five trials of the same color suggests that priming may have played a role. Although this is a viable point one should be cautious to interpret these results as such as there were only very few sequences of five consecutive trials which may make the data rather noisy (i.e. only 5.5% of the trials). Moreover it should be realized that there was no effect for sequences of less than five consecutive trials, which suggest that if an effect of priming exists it builds up rather slow.

### 3.3.3. Saccade latency

The ANOVA on the medians of saccade latency with Sequence Length (1, 2, 3, 4 or 5 consecutive trials) as a factor indicated that there was no significant effect of Sequence Length ( $F(4,52) = .279, p = .890$ ). All five conditions displayed a similar latency distribution. Fig. 10 shows the frequency distribution plot of saccade latency of Experiment 2.

## 4. Discussion

The aim of the present study was to systematically investigate the time course of top-down control on saccade averaging. In two experiments peripheral stimuli were presented in close proximity. In the first experiment there was either no target specified (i.e. participants were instructed to make a saccade to whatever appeared on the screen) or there was a specific target–distractor distinction with a red target and a green distractor. The results showed that in the conditions with a clear target instruction, shorter latency saccades showed a stronger global effect than longer latency saccades. This experiment also showed that even for the shortest latencies, task instruction affects the landing position. As we hypothesized that this effect was due to inter-trial priming



**Fig. 10.** Frequency distribution plot of saccade latency for Experiment 2. The mean value is given in the figure.

(Rastgardani et al., 2009; Theeuwes, 2010; Theeuwes, Reimann, & Mortier, 2006), we conducted a second experiment in which the relevant color varied from trial to trial. At the beginning of each trial an instructional word (red or green) was presented indicating the color of the target for that trial. Experiment 2 confirmed the existence of a global effect that decreased linearly with longer latencies and an effect of task instruction for all saccade latencies, including the fastest saccades. In addition, the second experiment showed that this shift towards the target cannot be attributed to priming as, even at the earliest stage, the global effect was significantly weakened by the instruction to make a saccade to the specified target. This effect was independent of priming as the number of preceding trials having the same color instruction did not affect this effect.

It can be questioned whether these results can be generalized to other conditions in which stimulus size, shape, salience or eccentricity are manipulated. Also, it is possible that the range of saccade latencies in the present study, which did not include the fastest saccades that have been observed in other studies, was already inside the top-down range. Judging from the strong incremental linear relation between saccade endpoint deviation and latency it can be expected that the time-course can be extended in a linear fashion outside this top-down range if saccade latencies are even shorter. The relatively slow saccades in this study might have been the result of the gap-paradigm that was used to force a wide range of latencies. Fixation off-set was highly random relative to stimulus onset and therefore provide no cue for saccade initiation which may have slowed responses. It is clear, however, that top-down information has an effect on saccade averaging well before the 300 ms latency mark that has been postulated until now (Ottes, Van Gisbergen, & Eggermont, 1985).

It is interesting to contrast the results of Experiment 2 against the findings of a recent study on visual priming (Meeter & Van der Stigchel, 2013). The Meeter and Van der Stigchel study showed that repeating the color of the target in consecutive trials resulted in a stronger deviation of the saccade endpoint towards the target (i.e. away from *perfect averaging*). Such an effect was not observed in our second experiment. A possible explanation for this discrepancy can be attributed to a fundamental difference between the two experimental paradigms. Even though Meeter and Van der Stigchel found a clear color priming effect on the saccade endpoint, the color was in fact task irrelevant as the target–distractor distinction was determined by the shape of the stimuli. In the present study, however, color was the only feature of interest and before each trial participants cued which color was relevant on that trial. It is feasible that the mere instruction of attending to one particular color overshadowed the repetition priming effect. The difference between these two studies suggests that when a feature is task relevant and part of the top-down instruction set, priming may not occur while bottom-up priming does occur when a feature is repeated from trial to trial when it is task irrelevant. This distinction gives an interesting insight into what can be the cause of early modulatory influence of top-down information on saccade programming.

The competitive integration model by Meeter, Van der Stigchel, and Theeuwes (2010) can account for the gradual built-up of the saccade endpoint deviation towards the target through the connection between the dorsolateral prefrontal cortex (DLPFC) and Frontal Eye Fields (FEF) and the midbrain structure known as the superior colliculus (SC). The SC, the area that is likely to be the major center for the control of eye movements (Schall, 1991), contains a retinotopically-organized motor map that integrates input from cortical areas such as the DLPFC, the FEF and the Secondary Eye Fields. The Meeter model predicts that FEF activity at the location of the target and the distractor initially increase in synchrony but after a certain time the activity associated with the distractor starts

to decline while the target activity continues to increase. Since the activity of target and distractor is combined and summed in the SC, as is proposed by Tipper's weighted average account (Tipper, Howard, & Jackson, 1997), it explains the gradual shift of the saccade landing position towards the target over time as seen in the experiments of this study. It does not fully account for the fact that this study shows an effect already present in the fastest trials in the experiments.

In a recent study, White et al. (2013) showed that when a salient task-irrelevant distractor was presented with abrupt-onset near a target, this distractor 'captured' visual attention. Extracellular recordings in the intermediate layers of the SC (SCi) of two monkeys showed two processes in response to a distractor near a target. First, a momentary goal-directed activation indicating competition between target and distractor, and second a presaccadic rebound in activation at the location of the target. This rebound activation resulted in a faster rise-to-threshold. It was this second activation that was responsible for the shorter latency compared to saccade latencies for distractors further away from the target. An explanation for the rebound activation that could be considered is that the receptive fields in the SCi are not fixed but may be modulated and put on edge by top-down information coming from experience-induced feature suppression of FEF neurons (Bichot, Schall, & Thompson, 1996; Schall et al., 2004). Perhaps the competitive integration model must be extended in such a way that experience or previously acquired knowledge about relevant stimulus features can integrate top-down information into the weighing of stimuli before a motor plan is devised.

In summary the present study demonstrates that top-down control influences the size of the global effect at a stage that is much earlier than has previously been established. The influence is linear over time and increases gradually with increasing saccade latency due to the gradual change in relative weight of the target and the distractor in a common motor map.

## References

- Aitsebaomo, A. P., & Bedell, H. E. (2000). Saccadic and psychophysical discrimination of double targets. *Optometry & Vision Science*, 77(6), 321–330.
- Bichot, N. P., Schall, J. D., & Thompson, K. G. (1996). Visual feature selectivity in frontal eye fields induced by experience in mature macaques. *Nature*, 381(6584), 697–699.
- Chou, I. (1999). Express averaging saccades in monkeys. *Vision Research*, 39(25), 4200–4216.
- Coëffé, C., & O'Regan, J. K. (1987). Reducing the influence of non-target stimuli on saccade accuracy: Predictability and latency effects. *Vision Research*, 27(2), 227–240.
- Coren, S., & Hoenig, P. (1972). Effect of non-target stimuli upon length of voluntary saccades. *Perceptual and Motor Skills*, 34(2), 499–508.
- Edelman, J. A., & Keller, E. L. (1998). Dependence on target configuration of express saccade-related activity in the primate superior colliculus. *Journal of Neurophysiology*, 80(3), 1407–1426.
- Fecteau, J. H., & Munoz, D. P. (2006). Salience, relevance, and firing: A priority map for target selection. *Trends in Cognitive Sciences*, 10(8), 382–390.
- Findlay, J. M. (1982). Global visual processing for saccadic eye movements. *Vision Research*, 22(8), 1033–1045.
- Findlay, J. M., & Blythe, H. I. (2009). Saccade target selection: Do distractors affect saccade accuracy? *Vision Research*, 49(10), 1267–1274.
- Findlay, J. M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioral and Brain Sciences*, 22(04), 661–674.
- Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology: Human Perception and Performance*, 28(5), 1039–1054.
- He, P., & Kowler, E. (1989). The role of location probability in the programming of saccades: Implications for "center-of-gravity" tendencies. *Vision Research*, 29(9), 1165–1181.
- Kopeck, K. (1995). Saccadic reaction times in gap/overlap paradigms: A model based on integration of intentional and visual information on neural, dynamic fields. *Vision Research*, 35(20), 2911–2925.
- McSorley, E., Cruickshank, A. G., & Inman, L. A. (2009). The development of the spatial extent of oculomotor inhibition. *Brain Research*, 1298, 92–98.
- McSorley, E., Haggard, P., & Walker, R. (2006). Time course of oculomotor inhibition revealed by saccade trajectory modulation. *Journal of Neurophysiology*, 96(3), 1420–1424.



- Meeter, M., & Van der Stigchel, S. (2013). Visual priming through a boost of the target signal: Evidence from saccadic landing positions. *Attention, Perception, & Psychophysics*, *75*(7), 1336–1341.
- Meeter, M., Van der Stigchel, S., & Theeuwes, J. (2010). A competitive integration model of exogenous and endogenous eye movements. *Biological Cybernetics*, *102*(4), 271–291.
- Menz, C., & Groner, R. (1987). Saccadic programming with multiple targets under different task conditions. *Paper presented at the eye movements: From physiology to cognition. Selected/edited proceedings of the third European conference on eye movements, Dourdan, France, September 1985* (p. 95).
- Ottes, F. P., Van Gisbergen, J. A. M., & Eggermont, J. J. (1985). Latency dependence of colour-based target vs nontarget discrimination by the saccadic system. *Vision Research*, *25*(6), 849–862.
- Rastgardani, T., Abegg, M., Lau, V., & Barton, J. J. (2009). Trial history biases the spatial programming of antisaccades. *Journal of Vision*, *9*(8), 445.
- Saslow, M. (1967). Effects of components of displacement-step stimuli upon latency for saccadic eye movement. *JOSA*, *57*(8), 1024–1029.
- Schall, J. D. (1991). Neuronal basis of saccadic eye movements. *Vision and Visual Dysfunction*, *4*, 388–442.
- Schall, J. D., Sato, T. R., Thompson, K. G., Vaughn, A. A., & Juan, C. (2004). Effects of search efficiency on surround suppression during visual selection in frontal eye field. *Journal of Neurophysiology*, *91*(6), 2765–2769.
- Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, *135*(2), 77–99.
- Theeuwes, J. (2013). Feature-based attention: It is all bottom-up priming. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *368*(1628), 1–11.
- Theeuwes, J., Reimann, B., & Mørtier, K. (2006). Visual search for featural singletons: No top-down modulation, only bottom-up priming. *Visual Cognition*, *14*(4–8), 466–489.
- Tipper, S. P., Howard, L. A., & Jackson, S. R. (1997). Selective reaching to grasp: Evidence for distractor interference effects. *Visual Cognition*, *4*(1), 1–38.
- Trappenberg, T. P., Dorris, M. C., Munoz, D. P., & Klein, R. M. (2001). A model of saccade initiation based on the competitive integration of exogenous and endogenous signals in the superior colliculus. *Journal of Cognitive Neuroscience*, *13*(2), 256–271.
- Van der Stigchel, S., Heeman, J., & Nijboer, T. C. W. (2012). Averaging is not everything: The saccade global effect weakens with increasing stimulus size. *Vision Research*, *62*, 108–115.
- Van der Stigchel, S., & Nijboer, T. C. W. (2011). The global effect: What determines where the eyes land. *Journal of Eye Movement Research*, *4*(2), 1–13.
- Van der Stigchel, S., & Nijboer, T. C. W. (2013). How global is the global effect? The spatial characteristics of saccade averaging. *Vision Research*, *84*, 6–15.
- Van Zoest, W., Donk, M., & Theeuwes, J. (2004). The role of stimulus-driven and goal-driven control in saccadic visual selection. *Journal of Experimental Psychology: Human Perception and Performance*, *30*(4), 746–759.
- Walker, R., Deubel, H., Schneider, W. X., & Findlay, J. M. (1997). Effect of remote distractors on saccade programming: Evidence for an extended fixation zone. *Journal of Neurophysiology*, *78*(2), 1108–1119.
- White, B. J., Marino, R. A., Boehnke, S. E., Itti, L., Theeuwes, J., & Munoz, D. P. (2013). Competitive integration of visual and goal-related signals on neuronal accumulation rate: A correlate of oculomotor capture in the superior colliculus. *Journal of Cognitive Neuroscience*, *25*(10), 1754–1765.