Gaze distractors influence saccadic curvature: Evidence for the role of the oculomotor system in gaze-cued orienting

Lauri Nummenmaa [a,*], Jari K. Hietanen [b,1]

[a] *Department of Psychology, University of Turku, Turku 20014, Finland*
[b] *Human Information Processing Laboratory, Department of Psychology, University of Tampere, Tampere 33014, Finland*

Abstract

We examined the role of the oculomotor system in gaze-triggered orienting of attention by measuring whether perceiving of task-irrelevant gaze distractors and peripheral spatial distractors influence saccadic curvature similarly. Participants performed reflexive, vertical saccades to designated target areas while their eye movements were recorded. Schematic faces with averted gaze or peripheral boxes were presented before or simultaneously (-100 ms/0 ms SOAs) with the imperative signal. Gaze distractors caused the saccades to curve away from the distractor direction at both SOAs and peripheral distractors only at the 0-ms SOA. The results imply that gaze-cued shifts of visual attention involve both cortical attention orienting systems and subcortical oculomotor systems.
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1. Introduction

Perceiving another person's averted gaze orients covert attention to the location of the gaze. Studies using a so called gaze-cuing paradigm (e.g., Driver et al., 1999; Friesen & Kingstone, 1998; Hietanen, 1999) have demonstrated reaction time benefits for detecting peripherally presented targets correctly cued by a centrally shown, laterally gazing face as a cue stimulus. The reaction time benefits occur when the time-interval between the presentation of the gaze cue and target is short (even less than 100 ms, Hietanen & Leppänen, 2003), and when the direction of perceived gaze is known to be spatially non-predictive (Friesen & Kingstone, 1998) or even counterpredictive (Driver et al., 1999; Friesen, Ristic, & Kingstone, 2004). Thus, attention orienting triggered by another person's gaze seems to fulfil

the criteria for automatic attention orienting (Friesen & Kingstone, 1998; Friesen et al., 2004).

Functional magnetic resonance imaging (fMRI) studies have demonstrated that specialized cortical networks, especially in the superior temporal sulcus and intraparietal sulcus are likely to be involved in perception of gaze direction and gaze-cued orienting (George, Driver, & Dolan, 2001; Hoffman & Haxby, 2000; Hooker et al., 2003; Kingstone, Tipper, Ristic, & Ngan, 2004; Pelphrey, Singerman, Allison, & McCarthy, 2003; Pelphrey, Viola, & McCarthy, 2004). But does reflexive gaze-cued attention orienting involve engagement of the subcortical oculomotor system? Shifts of overt attention are accompanied by saccades, and attention orienting and saccade programming are known to share common neural substrates (Rizzolatti, Riggio, Dascola, & Umiltá, 1987; Rizzolatti, Riggio, & Sheliga, 1994; Sheliga, Riggio, Craighero, & Rizzolatti, 1995; see also Awh, Armstrong, & Moore, 2006 for a review of recent evidence). Thus, if presentation of a gaze direction cue exerts influence on such features of saccadic responses which are known to be under the control of the subcortical

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* Corresponding author. Fax: +358 2 333 5060.
  E-mail addresses: latanu@utu.fi (L. Nummenmaa), psjahi@uta.fi (J.K. Hietanen).
[1] Fax: +358 3 3551 7345.

oculomotor systems, one can infer that these oculomotor systems are also involved in the automatic attention orienting triggered by gaze stimuli.

Friesen and Kingstone (2003) investigated whether the superior colliculus (SC) is involved in reflexive gaze-cued attention orienting using a gaze-cuing paradigm (SOA:s of 500 ms and 1000 ms) with either a manual localization or saccade response task. Additionally, fixation offset/overlap manipulation was employed. Fixation offset before or simultaneously with saccade target onset is known to facilitate saccadic reaction times because the offset disengages the SC (Dorris & Munoz, 1995). Friesen and Kingstone hypothesized that if gaze-cued orienting would involve the SC, (i) the fixation offset effect (FOE, i.e., the response time difference between the fixation offset and overlap conditions) would be smaller after cues with averted than straight gaze and (ii) the response time difference between cued and uncued trials would be larger for saccadic than for manual responses. However, the results demonstrated that the FOE was of similar size for cued and straight gaze trials, and the gaze-cuing effect was actually smaller for saccadic than manual responses, suggesting that the oculomotor system might not be involved in reflexive gaze-cued orienting and that such orienting is based on cortical processes.

Nonetheless, in a gaze cuing paradigm participants have a tendency to make saccades in the direction of the gaze cues before the presentation of the target (Mansfield, Farroni, & Johnson, 2003), suggesting oculomotor engagement. In a recent study (Ricciardelli, Bricolo, Aglioti, & Chelazzi, 2002) participants made saccades to the left or right depending on the change of the colour of the initial fixation target. A gaze distractor looking at congruent or incongruent direction with respect to the direction instructed by the colour cue was presented either before, simultaneously with, or after the colour cue. The results showed that the proportion of misdirected saccades was significantly higher in the incongruent than congruent conditions when the gaze distractor was presented either 75 ms before, simultaneously with, or 50 ms (Experiment 1) after the onset of the colour cue. When the gaze distractor was presented 150 ms before or 75 ms after the colour cue, no such effect was any more observed. These results implied that the activation of the oculomotor system is reflected in the task-instruction triggered saccades only if the gaze cue is presented within a critical time window of −75 to +50 ms around the onset of the saccade instruction cue.

Considering the somewhat conflicting results as presented above, we felt that another type of a paradigm would be welcome to study whether seeing an averted gaze automatically activates the oculomotor system. Visual attention orienting involves the activation of the oculomotor system which, in turn, influences, among other things, the curvature of saccades (for a review, see Van der Stigchel, Meeter, & Theeuwes, 2006). Saccades curve away form the location

where attention has recently been allocated (Rizzolatti et al., 1994; Sheliga et al., 1995; Sheliga, Riggio, & Rizzolatti, 1994). In the basic paradigm (Sheliga et al., 1995), participants made saccades to target boxes located either above, below, left, or right to the initial fixation point. Saccade direction was specified with an imperative signal that was presented in the visual periphery, orthogonal to the direction of the subsequent saccade. Prior to presenting the imperative signal, the participants were informed with a centrally presented cue where the imperative signal would be presented. The participants were instructed to allocate covert attention to the cued location, and wait for the presentation of the imperative signal to make a saccade. The results demonstrated that saccades curved away from the voluntarily attended location.

Saccades also curve away from irrelevant spatial distractors presented in the visual periphery (Doyle & Walker, 2001, 2002; Godijn & Theeuwes, 2004). In these experiments, the participants were instructed to ignore the spatial distractors and perform saccades according to the imperative signal. The results indicate that the curvature of saccades is also influenced by reflexive shifts of attention. The curvature away from the distractor has been explained by the competing interactions that operate in the neural map that specifies the saccade goals (e.g., Godijn & Theeuwes, 2002). Competing stimuli activate separate populations of neurons. If a distractor is presented with an instruction to perform a saccade, the inhibition of the response to the spatial location indicated by the distractor reduces the activity of neurons associated with programming the response to the distractor below baseline level. Consequently, this causes the task-instructed saccade to curve away from the distractor.

We assessed whether the oculomotor system is involved in gaze-cued orienting by measuring the curvature of saccades executed in the context of presentation of task-irrelevant gaze distractors. Participants were instructed to ignore the gaze distractors and make vertical saccades from a central fixation circle to target crosses appearing abruptly at the visual periphery. As the saccadic curvature reflects reduction in the activity of neurons associated with programming the saccade to the direction of the reflexive attention shift, the saccades were expected to curve away from the direction indicated by the gaze. To make our results comparable with those obtained in the peripheral distractor paradigm, a peripheral distractor condition was also employed. Also, two SOAs were used: −100 and 0 ms (the onset of the distractor was time-locked to the onset of the imperative signal indicating the target of the saccade to be made). Selection of these SOAs was based on the findings by Ricciardelli et al. (2002). Because there are large individual differences in the magnitude and direction of saccadic curvature under normal conditions (see e.g., Erkelens & Sloot, 1995), a control condition was employed in which participants performed reflexive vertical saccades in the absence of gaze/peripheral distractors.

2. Method

2.1. Participants

Eighteen volunteer students (14 females) with a mean age of 23 years from the University of Turku participated in the experiment. Participants' visual acuity was tested with a standard Snellen chart to ensure normal or corrected-to-normal ($\geqslant 1$) visual acuity. Of the 20 persons originally participating in the study, one had to be excluded due to self-reported heterotropia and one due to equipment malfunction.

2.2. Apparatus

Stimuli were presented on a 20 in. ViewSonic monitor with a 2 GHz Pentium III computer. Participants' eye movements were recorded with an EyeLink II eye tracker connected to a 2 GHz Pentium III computer. The sampling rate was 500 Hz, and the spatial accuracy was better than 0.5°, with a 0.01° resolution in pupil tracking mode.

2.3. Stimuli

Fixation marker was a black circle with white center (diameter 0.5°, the standard drift correction circle for EyeLink II). The initial display (see Fig. 1) consisted of the fixation circle and a black line drawing of a round schematic face subtending 11° and centered in the middle of the screen. The eyes subtended 1.6° and were located on the central horizontal axis at the distance of 1.5° from the central vertical axis. The pupils were not initially displayed but appeared according to the SOA of the trial. The imperative signal was a black cross (diameter 2°) located at the central vertical axis 14° to top/bottom of the screen from the central horizontal axis. The gaze distractor signal was an appearance of the pupils gazing right or left. Black-filled circles inside the eyes represented pupils. They subtended 0.8°, were centered vertically to the eyes and were just touching right or left of the eyes. The peripheral distractor signal was a black target box (diameter 2°) located at the central horizontal axis 14° to left/right from the central vertical axis.

2.4. Design

The experimental design was within-subjects 2 (SOA: −100 ms, 0 ms) × 2 (distractor hemifield: left, right) × 2 (distractor type: gaze, peripheral).

2.5. Procedure

Participants were tested individually, and testing time totaled approximately 1 h per participant. Upon arrival, participants' visual acuity was measured with a Snellen chart at the distance of 6 m. Participants were given informed consent and explained that the study was concerned about vertical eye movements. Participants were seated in a comfortable chair approximately 60 cm apart from the screen and given instructions on how to perform the experimental trials. They were stressed that the schematic faces and peripherally presented boxes they were going to see were unrelated to the saccade task in the experiment and could simply be ignored. Finally, 10 practice trials were performed. After the practice trials, the eye tracker was calibrated. The calibration was accepted if the average error was less than .5° of visual angle.

Before each trial (see Fig. 1), a fixation point appeared on the screen, and the participant had to focus his/her gaze at the center of the circle. When the participant's eye was fixed on the circle, the experimenter initiated the trial. Next, the initial face display appeared. After a random period of 800–1200 ms, the distractor (gaze or peripheral, according to trial type) or the imperative signal with the distractor appeared on the screen depending on the SOA of the trial. The participants were instructed to ignore the distractor, perform a saccade to the imperative signal (i.e., target cross) as soon as it appeared, and maintain fixation until the imperative signal disappeared. After 1500 ms, the stimulus display was replaced with the fixation circle, and the next trial was initiated by the experimenter when the participant was looking at the center of the fixation circle. Each participant performed four blocks of the task with distractors. Each of these consisted of 8 trials of each type totaling 64 trials per block. Moreover, each participant performed a control block of 32 saccades without distractors. On these trials, the schematic face without pupils was displayed throughout the trial, and the imperative signal was presented as above. The total number of trials was 288 (32 trials of each type). There was a short break between the blocks followed by recalibration of the eye tracker. Upon completion of all the trials, the participants were debriefed about the purpose of the experiment.

2.6. Data analysis

Three types of eye movement measures were gathered: (1) the coordinates of gaze, (2) the timestamp of every data sample, and (3) an indication whether participant was making a fixation, saccade, or a blink during current eye sample. A custom computer program was used to transform these measures into four variables used in the analysis: (1) saccadic latency, i.e., the time taken to initiate the saccade after the presentation of the imperative signal, (2) the amplitude of the saccade in degrees,
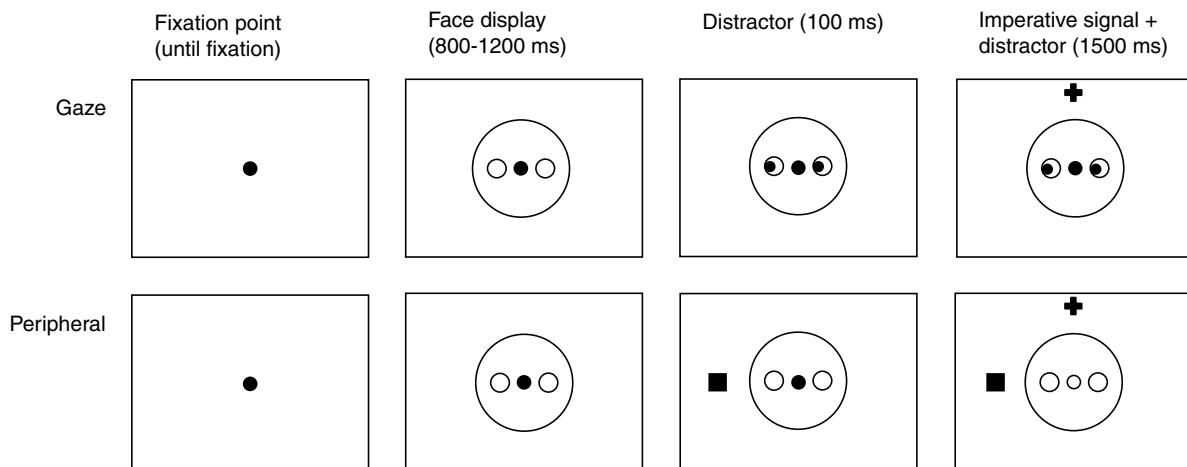

Fig. 1. Time sequence of events on trials with gaze and peripheral distractors at −100 ms SOA. On trials with 0 ms SOA the distractor and imperative signal appeared simultaneously.
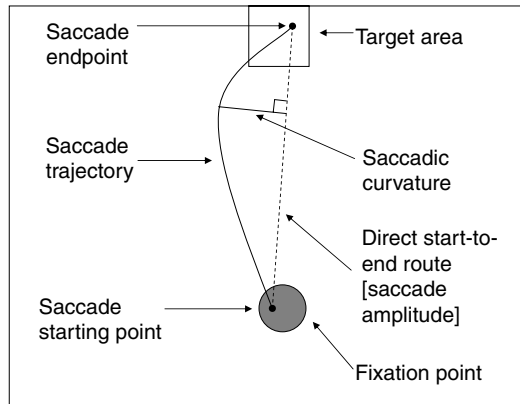
Fig. 2. Computing the signed saccadic curvature as the peak deviation from the direct start-to-end route.

(3) the *x*-deviation of the saccade endpoint from the center of the target cross in degrees, and (4) the signed curvature of the saccade (see Fig. 2). The signed curvature of a saccade was computed as the peak deviation of the saccade trajectory from the interpolated direct start-to-end route. To balance the potential effects of the saccade amplitude on the curvature, the signed curvature measure was divided by the saccade amplitude to obtain a ratio value of curvature per unit of amplitude. Saccades with a curvature to the right were given a plus sign and those with a curvature to the left a minus sign. Finally, the signed curvature of saccades in the control condition was subtracted from those in the experimental conditions. Therefore, the final signed curvature represents how much and into which direction the distractors caused the saccades to curve with respect to the curvature occurring under nondistracted conditions.

As the minimal saccadic latency is typically at least 150 ms (Rayner, 1998), saccades with latencies less than 100 ms were defined as anticipations and omitted from the analysis. If the latency was 2.5 standard deviations above the individual mean, saccade was defined as retardation and omitted. Saccades made to wrong targets or falling more than 2° outside the target area were labeled as errors, and saccades with amplitudes less than 10° were considered undershoots, and both were omitted. As the upper edge of the target cross was located only 0.5° from the border of the display, no saccades were classified as overshoots.

3. Results

The means and 95% confidence limits of the saccade latencies, saccade amplitudes, and endpoint *x*-deviation for the different SOA × distractor hemifield × distractor-type combinations are presented in Table 1. The respective results regarding the signed curvature of the saccades are

presented in Fig. 3. All the eye movement measures were subjected to 2 (SOA: −100 ms, 0 ms) × 2 (distractor hemifield: left, right) × 2 (distractor type: gaze, peripheral) repeated measures ANOVAs.

The saccadic latency was influenced by SOA, $F(1, 17) = 32.64$, $p < .01$, $\eta_p^2 = .66$. Latencies were shorter on −100-ms than on 0-ms trials (216 vs. 244, respectively). None of the other main effects or interactions was significant. Saccade amplitude was not affected by SOA, distractor hemifield, distractor type, or their interactions. The endpoint *x*-deviation was affected by the SOA × distractor hemifield × distractor-type interaction. Multiple comparisons (Bonferroni corrected *F* tests) showed that the endpoint *x*-deviations were significantly different after left- and right-sided peripheral distractors presented at the −100-ms SOA. After left sided distractors, the saccade endpoints deviated towards the right hemifield (0.140°), whereas after right-sided distractors the saccade endpoints deviated towards the left hemifield (−0.163°).

Most importantly, the signed curvature of the saccades was influenced by the distractor hemifield as expected, $F(1, 17) = 4.86$, $p = .04$, $\eta_p^2 = .22$. Left-hemifield distractors caused saccades to curve to right ($M = 0.001$), whereas right-hemifield distractors resulted in leftward curvatures ($M = -0.001$), with highly similar absolute curvature values for distractors presented in the left/right hemifield. Inspection of Fig. 3 shows that, for both the gaze and peripheral distractors, the effect of the distractor hemifield was particularly clear at the 0-ms SOA. However, the main effects of SOA and distractor type, or any of the interactions between the main effects were not statistically significant.

4. Discussion

We examined if the oculomotor system is reflexively activated upon perception of averted gaze by measuring the curvature of reflexive vertical saccades that participants made after presentation of task-irrelevant gaze or peripherally presented spatial distractors. The results provided evidence for a view that the oculomotor system is involved also in gaze-triggered shifts of attention. Covert orienting of spatial attention by irrelevant peripheral distractors is

Table 1
Means and 95% confidence limits of saccadic latencies (ms), amplitudes (°), and endpoint *x*-deviations (°) by SOA, distractor hemifield, and distractor type

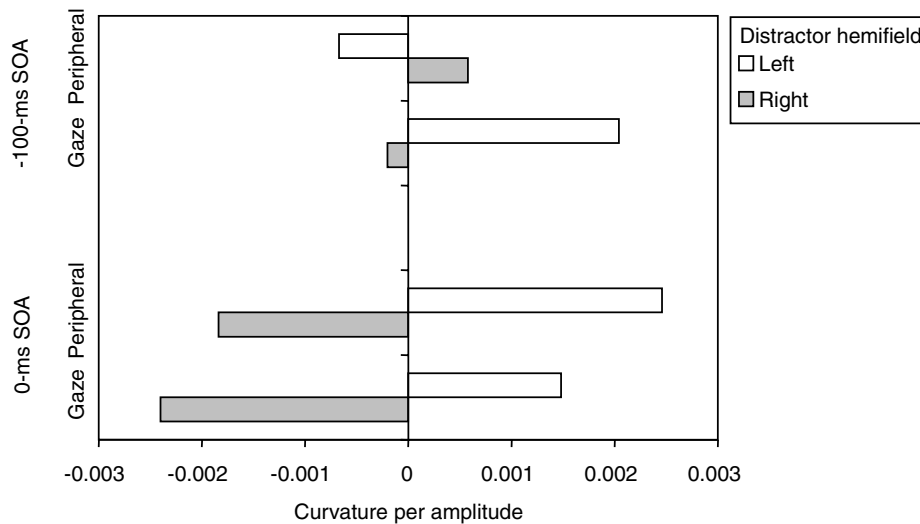|	−100 ms SOA		0 ms SOA	
	Left	Right	Left	Right
Gaze distractors				
Latency	218 ± 19	216 ± 21	246 ± 21	241 ± 19
Amplitude	14.111 ± 0.314	14.237 ± 0.263	14.297 ± 0.232	14.198 ± 0.274
x-deviation	−0.114 ± 0.227	−0.101 ± 0.241	−0.111 ± 0.226	−0.106 ± 0.211
Peripheral distractors				
Latency	213 ± 21	215 ± 23	241 ± 18	247 ± 19
Amplitude	14.180 ± 0.205	14.075 ± 0.293	14.162 ± 0.201	14.165 ± 0.232
x-deviation	0.140 ± 0.310	−0.163 ± 0.234	−0.103 ± 0.255	−0.056 ± 0.225

Fig. 3. Signed saccadic curvature as a function of SOA, distractor type, and distractor hemifield.

known to activate the oculomotor system and influence the curvature of orthogonal saccades (Doyle & Walker, 2001, 2002; Godijn & Theeuwes, 2004, Experiment 1). As our data demonstrated that such a saccadic curvature also results from centrally presented gaze distractors presented at both −100-ms and 0-ms SOAs, the current results suggest that the gaze cues activate the oculomotor system, and that the oculomotor system is involved in gaze-cued orienting. The gaze distractors caused the saccades to curve away from the gaze direction: leftwards-gazing face caused saccades to curve to right and vice versa. The curvature away from the distractor hemifield results from inhibition of the response to the spatial location indicated by the distractor, which reduces the activity of neurons associated with programming the response to the distractor (Godijn & Theeuwes, 2002). As our participants had to ignore the gaze display and never actually make a saccade to the gaze direction, the results provide strong evidence for the bottom-up nature of the oculomotor responses occurring upon eye gaze perception.

Although the analysis of the saccadic curvature yielded a statistically significant main effect for distractor hemifield only and no interactions between SOA, distractor hemifield, and distractor type, inspection of Fig. 3 reveals that, at the −100-ms SOA, peripheral distractors seemed to cause saccades to curve slightly to the hemifield in which the distractor was presented. This result seems to be in contrast with the previous studies which have demonstrated that reflexive saccades curve away from peripheral distractors at the SOAs of 0 ms (Doyle & Walker, 2001, 2002, Experiment 2) and −100 ms (Doyle & Walker, 2002, Experiment 3, Godijn & Theeuwes, 2004, Experiment 1). However, in the experiments by Doyle and Walker (2001, 2002), for example, the distractors were not presented at the central horizontal axis but instead they were located ±6° (2001) or ±7.1° (2002) from the axis. No interactions between the saccade target hemifield (upper/lower) and distractor hemifield (upper/lower) were demonstrated in the

2002 study. On the contrary, in the 2001 study, Doyle and Walker showed that the distractors influenced saccadic curvature when they were presented in the same upper/lower hemifield with the target, but not when presented in the opposite hemifield. Therefore, it is possible that the influence the peripheral distractors exert on saccade programming decreases when the distractors are presented closer to the horizontal axis through the initial fixation. Importantly, the present results showed that, at the −100-ms SOA, the x-coordinate of the saccade endpoint was shifted towards the opposite visual field in which the peripheral distractor appeared. This suggests that, in the present experimental design also, the peripheral distractors presented at the negative SOA exerted some influence on the saccade programming.

Interestingly, a recent study (McSorley, Haggard, & Walker, in press) demonstrated that saccade latency modulates saccadic curvature. Namely, saccades with short latencies (<200 ms) curved towards distractors, as distractor-related activity in the saccade map has not yet been suppressed. On the contrary, saccades with longer latencies (>200 ms) curved away from the distractor, as the inhibitory processes have had time to suppress the distractor-related activity below baseline level. In the current study, a similar pattern (though not statistically significant) of curvature also emerged for the peripheral distractors. Saccade latencies were shorter for the −100-ms SOA, and these saccades curved slightly towards the peripheral distractors. Therefore, we consider that our results generally fit with those reported in previous studies investigating the effect of task-irrelevant peripheral distractors on saccadic curvature (Doyle & Walker, 2001, 2002; Godijn & Theeuwes, 2004, Experiment 1; McSorley et al., in press).

According to the premotor theory of attention (Rizzolatti et al., 1987), attention is oriented to a spatial location when an oculomotor program for making a saccade to the target is programmed. In general, our data also provided support for the premotor theory of attention by demon-

strating that the perception of centrally presented unattended directional signals resulted in a reflexive oculomotor response manifested in the saccadic curvature. It has been suggested that the curvature results from competing saccade goals at the SC (McPeek, Han, & Keller, 2003). Thus, the present findings could be argued to demonstrate that the SC is involved even in perception of centrally presented, completely irrelevant directional stimulus. Together with the earlier ones reporting gaze cue-driven saccades (Mansfield et al., 2003; Ricciardelli et al., 2002), our results seem to imply that the gaze-cued attention shifts involve not only cortical attention orienting systems but also subcortical oculomotor systems. In this respect, these results are somewhat contradictory with those by Friesen and Kingstone (2003) who used a fixation offset manipulation in a gaze-cuing paradigm and reported results suggesting that the oculomotor superior colliculus was not involved in orienting of attention by gaze cues. However, it must be emphasized that our results do not mean that cortical networks are not involved in orienting of attention by gaze cues. Rather, we interpret our results to provide support for a notion that gaze cues affect the cortical attentional systems which, in turn, modulate the oculomotor system at the level of the SC.

But is the reported effect really due to the perception of the distractor stimulus as a face with averted gaze? One could argue that two asymmetrically presented circles (pupils) would be a sufficiently salient signal to trigger the attention to the direction of the circles. However, there is evidence showing that the attention orienting effects of eye gaze are not due to the low-level geometry/asymmetry of the stimulus. Presenting photographic negatives of faces with averted gaze abolishes the gaze cuing effect, thus demonstrating that the effect is also dependent on the iris–sclera contrast (Tipples, 2005). Moreover, Ristic and Kingstone (2005) have shown that gaze cuing can be dependent on whether an ambiguous stimulus is perceived as a gaze cue (a hat pulled down to the eyes) or as another type of directional cue (a car with eccentric wheels). Therefore, it is fairly safe to assume that the oculomotor activity observed in the current study also reflects the processing of gaze information.

To sum up, our results suggest that perceiving an averted gaze stimulus exerts influence on programming of reflexive saccades. Perceiving of another person's gaze does not merely involve visual analysis of the gaze direction, but maps this information into a motor representation in the perceiver's oculomotor system. This suggests that gaze-cued attention orienting involves the functioning of subcortical oculomotor systems as well as cortical attention controlling systems.

Acknowledgment

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