The Role of Awareness in Processing of Oculomotor Capture: Evidence from Event-related Potentials

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Abstract

■ Previous research has shown that task-irrelevant onsets trigger an eye movement in their direction. Such oculomotor capture is often impervious to conscious awareness. The present study used event-related brain potentials to examine how such oculomotor errors are detected, evaluated, and compensated for and whether awareness of an error played a role at any of these stages of processing. The results show that the early processes of error detection and correction (as represented by the error-related negativity and the parietal N1) are not directly affected by subjective awareness of making an error. Instead, they seem to be modulated by the degree of temporal overlap between the programming of the correct and erroneous saccade. We found that only a later component (the error-related positivity [Pe]) is modulated by awareness of making an erroneous eye movement. We propose that awareness of oculomotor capture primarily depends on this later process. ■

INTRODUCTION

Our environment presents us with a variety of distractions that can interfere with achievement of even simple goals, such as crossing the street or reading a book. To ensure that we meet our goal, the information relevant to our goals and intentions needs to be selected, whereas irrelevant information needs to be ignored, especially when it disrupts our plans and actions. Continuous interruptions and adjustments of ongoing performance, as for example, in maintaining a car in the center of a lane while driving, often seem to occur with little or no awareness. An important question addressed in this study is the role of awareness in detection, evaluation, and subsequent compensation for such erroneous events (i.e., "slips").

Studies in the neuroscience of cognitive control suggest that error processing comprises part of a broader action-monitoring system, with the anterior cingulate cortex being a critical region in the brain network subserving error processing (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). However, at present, only a few studies have examined a critical question of how this anterior error processing system is affected by the conscious experience of making an error.

Specifically, studies using event-related potentials (ERPs) have examined whether two error-related components (the error-related negativity [ERN] and the error-related positivity [Pe]) in the response-locked waveforms were modulated by awareness of an erroneous eye movement (Endrass, Franke, & Kathmann, 2005; Nieuwenhuis, Ridderinkhof, Blow, Band, & Kok, 2001) or of an erroneous manual response (O'Connell et al., 2007). The ERN (also sometimes referred to as the Ne) is a negative component recorded over frontal–central electrode sites about 100 msec after an incorrect response. Its timing and sensitivity to errors led to the suggestion that it manifests an outcome of a rapid automatic matching of executed and required responses (Coles, Scheffers, & Holroyd, 2001; Gehring, Goss, Coles, Meyer, & Donchin, 1993; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991). Alternatively, the ERN has been suggested to reflect the amount of conflict between correct and erroneous responses (van Veen & Carter, 2002) or an error in reward prediction (Holroyd & Coles, 2002). The functional significance of the Pe component, on the other hand, remains less clear. Its late onset (300–400 msec) and its diffuse scalp distribution suggest that it reflects different processes than the ERN. Several hypotheses regarding the Pe have been brought forward. Although, so far, there is little support for the hypotheses that the Pe reflects affective processing of errors or behavioral post-error adaptation, there is accumulating evidence for a relation of the Pe to motivational significance of error or conscious error recognition (for the latest review, see Overbeek, Nieuwenhuis, & Ridderinkhof, 2005).

In fact, the first study that examined the relationship between error processing and awareness (Nieuwenhuis et al., 2001) found that the Pe, but not the ERN, amplitude was influenced by participants' awareness of an erroneous eye movement in the antisaccade task (Munoz & Everling, 2004; Hallet, 1978). These results

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were recently replicated in a stop-signal saccade paradigm (Endrass et al., 2005) and in a go/no-go task with manual responses (O'Connell et al., 2007). A recent fMRI study (Hester, Foxe, Molholm, Shpaner, & Garavan, 2005) also found no difference in anterior cingulate cortex activation between the aware and unaware erroneous manual responses.

Compared to other tasks, the antisaccade task seems more appropriate to study awareness of error processing because it allows for a representation of a correct response (i.e., moving the eyes away from the cue), allows for error corrections, and because erroneous saccades go unnoticed more often than manual responses. However, binary subjective awareness ratings in the antisaccade task might be a very crude measure of awareness because participants are always aware of the onset cue and have to attend to it in order to successfully perform the task. Given the large overlap between the attention and the eye movement systems (Corbetta, 1998), the difference between the task-required attentional shift and erroneous gaze shift in the antisaccade task might be difficult to dissociate consciously. It is possible that the failure to find a difference between the ERN for the aware and unaware errors in the study by Nieuwenhuis et al. (2001) (and perhaps in the other studies) was due to the inaccurate awareness ratings.

Therefore, one goal of the present study was to examine the findings regarding the role of awareness in performance monitoring using a different paradigm. We used the oculomotor capture paradigm (Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; Theeuwes, Kramer, Hahn, & Irwin, 1998), in which participants' goal was to find a color singleton and to move their eyes to its location. On some trials, a new distractor circle, presented with abrupt onset, was added to the display (see Figure 1). Participants typically move their eyes to the onset distractor on 30% to 40% of the trials but are mostly not aware of the onset distractors or their eye movements to them (before moving the eyes to the color singleton target location). Importantly, given that the onset distractor is completely irrelevant (i.e., it predicts neither the location nor the correct response to the target), it does not need to be consciously perceived—as is the case for the onset cue stimulus in the antisaccade task.

Thus, use of the oculomotor capture task should allow for better separation between the aware and unaware capture errors, which would be evident in very short fixation durations on the onset distractors (<100 msec) for the unaware errors (Godijn & Theeuwes, 2002), and also possibly smaller saccade amplitude and angular deviation from the target. In an effort to obtain an indication of participants' level of awareness concerning their eye movements, we obtained binary subjective awareness judgments following each experimental trial. To have a continuous measure of awareness, we also collected participants' confidence ratings in their judgment at the end of every trial (see Figure 1). If there is a clear separation

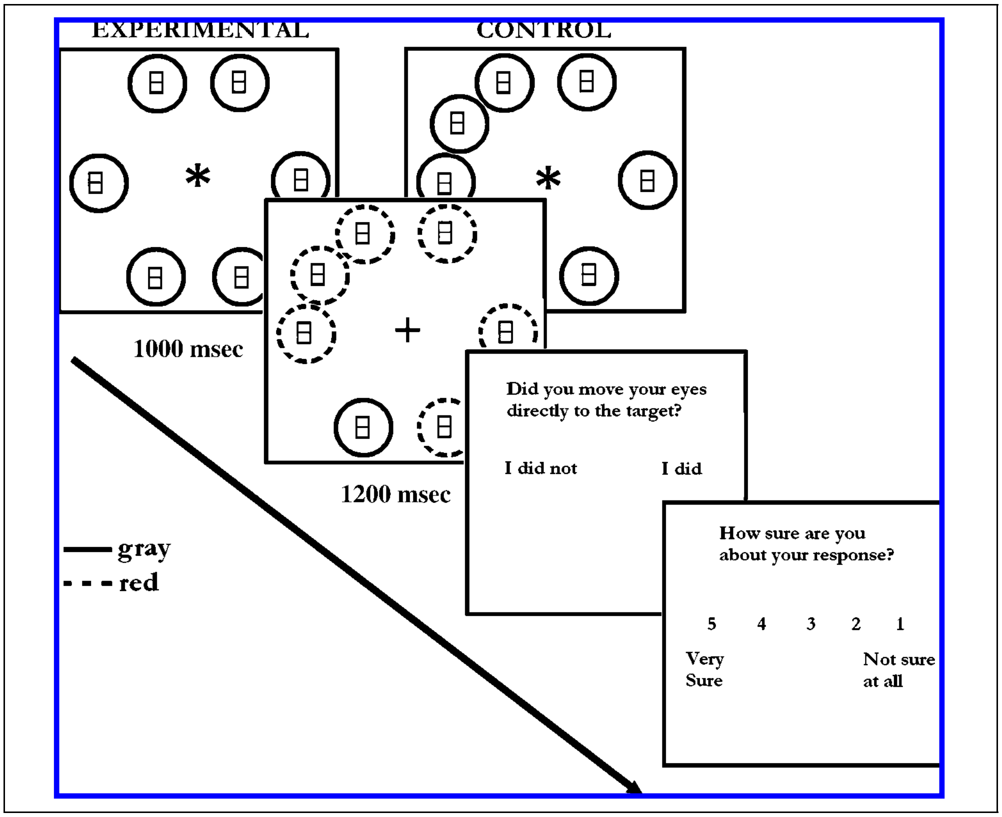

Figure 1. Examples of the displays used in the experiment (not drawn to scale).

between the aware and unaware errors in our paradigm, we expect that participants should be confident in their responses, even when reporting making a correct response, while actually making an error (the unaware error). However, participants should still be less confident after making ''unaware'' than ''aware'' judgments. If awareness of making an error in this task affects the error detection system, we expected the ERN to be different for the aware and unaware capture errors. However, we also expect to replicate previous findings (O'Connell et al., 2007; Endrass et al., 2005; Nieuwenhuis et al., 2001) and find a larger Pe for the aware than for unaware capture errors.

The second goal of the study was to examine the involvement of the so-called posterior error system in the oculomotor capture paradigm (Desmurget & Grafton, 2000). Until recently (Krigolson & Holroyd, 2006), this error system, located primarily in the posterior parietal cortex, has been studied separately from the anterior error system (described above) in the tasks similar to the oculomotor capture paradigm (i.e., ''double-step'' paradigm). The posterior system is involved in on-line monitoring and correction of movements based on both efferent copies and peripheral feedback, and its operation does not seem to rely on subjective awareness (Johnson, van Beers, & Haggard, 2002; Pisella et al., 2000). In our previous study using a similar paradigm (Belopolsky & Kramer, 2006), we observed a small negative-going component peaking around 140 msec after an erroneous saccade at parietal electrode sites. Interestingly, a similar parietal component was also seen in a study by Krigolson and Holroyd (2006) using a continuous manual tracking task and with a slightly more fronto-central distribution in the study by Nieuwenhuis et al. (2001, Figure 4). If this component is related to the error processing by the posterior error system, we expect to find it in the present study as well, however, it is not clear whether it would be modulated by the awareness of the erroneous saccade (Godijn & Theeuwes, 2002).

The third goal of the study was to further verify the theoretical meaning of the observed ERP components by correlating their amplitudes with performance measures. Based on previous studies (Holroyd & Coles, 2002; Coles et al., 2001; Bernstein, Scheffers, & Coles, 1995), we predicted that the ERN amplitude (as the index of mismatch) should increase with the magnitude of error, as manifested by angular error of the saccade from the target or by the amplitude of the erroneous saccade. Because longer fixation duration on the distractor has been previously linked to adjustment of the oculomotor program (Godijn & Theeuwes, 2002), a greater involvement of the posterior error system is expected and the N1 amplitude should increase with the fixation duration on the onset distractor (prior to a corrective saccade to the color singleton target). Based on the previous findings that the Pe component reflects a conscious decision about whether the error had occurred (Nieuwenhuis et al., 2001), we predicted that it might be positively correlated with the awareness decision confidence measures.

METHODS

Participants

Sixteen right-handed individuals, between 18 and 30 years old (average age = 21 years, 8 men), were paid for their participation in the study. All participants had normal or corrected-to-normal visual acuity and normal color vision (Ishihari Color Blindness Test, 1989). Five participants were replaced due to an insufficient number of saccade direction errors (<2%).

Stimuli and Procedure

The stimuli were presented in 16-bit color depth on 21-in. SVGA monitor at a distance of 70 cm. Participants viewed displays containing six gray circle premasks (3.5° in diameter, 1 pixel wide, luminance 21 cd/m^2) presented on an imaginary circle with a radius of 9.7° (Figure 1). Each circle contained a small gray figure 8 (0.1° by 0.2°) to assist fixation in the center of the circle. On half of the trials, six circles appeared at the clock positions 1, 3, 5, 7, 9, and 11 (Arrangement 1) and on the other half at positions 2, 4, 6, 8, 10, and 12 (Arrangement 2).[1] Positions 3, 6, 9, and 12 were never target positions. After 1000 msec, all the gray circle premasks but one changed color to an equiluminant red. Participants were instructed to move their eyes to the uniquely colored gray circle as fast as possible and as soon as they detected the color or fixation point (0.3°) change (Figure 1). On 75% of the trials, an extra red circle was added to the display simultaneously with the color change (onset present condition). This extra circle could appear at the clock positions 2, 4, 8, and 10 for Arrangement 1, and at the positions 1, 5, 7, and 11 for Arrangement 2, with a constraint that it had to be either 90° or 150° away from the gray circle. The onset never served as a target. On 25% of the trials, a gray premask was presented at the same extra location (no-onset control condition). After 1200 msec, the search display was replaced with the awareness rating display. Participants had to press the ''z'' key if they thought they did not move their eyes directly to the target or to press the ''?/'' key if they thought that they did move their eyes directly to the target. Immediately after making a response, they had to rate their confidence on a scale of 1 to 5, with 5 indicating the highest confidence. Participants completed 10 practice and 672 experimental trials (28 blocks). They received feedback about their average saccadic latency every block and were encouraged to increase the speed of their eye movement.

Recording and Analysis

Eye movements were recorded with an ASL 504 remote eye tracker at 60 Hz. An eye movement was considered a saccade when the movement distance from the center fixation exceeded 1.5°. The object to which the saccade was initially directed was determined by the first data point of the eye movement. A saccade was assigned to a particular object if it was ±22.5° to the left or to the right of that object. Because the fixations on the onset can be quite brief (<100 msec), fixation was calculated to start when two consecutive data points were within 0.5° of each other, and it ended when any point that followed was more than 0.5° away from the average of all points previously accumulated for that fixation.

The electroencephalogram (EEG) was acquired from 32 electrodes located at standard positions according to the extended International 10–20 System (F7, F3, Fz, F4, F8, FT7, FC3, FC4, FT8, T3, C3, Cz, C4, T4, TP7, CP3, CP4, TP8, T5, P3, Pz, P4, T6, OT1, OT2, O1, Oz, and O2) with a bandpass of 0.1–50 Hz and digitized at 250 Hz (Compumedics Neuroscan; Charlotte, NC, USA). The gain was 5000 for the EEG channels and 500 for the electrooculogram channels. During the recording, left mastoid (A1) served as a reference electrode. Prior to averaging, data were re-referenced off-line to the algebraic average of two mastoids, $X_t - \left(\frac{1}{2}\right)(A2_t)$, where X is the electrode and t is the time point (msec).

EEG data were analyzed using Scan 4.2 (Compumedics Neuroscan) and EEGLAB toolbox (Delorme & Makeig, 2004). All ERP waveforms were time-locked to the onset of the first saccade. Eye blinks, eye movements, muscle and line noise artifacts were corrected using independent components analysis (ICA) algorithm (Jung et al., 2000). ICA is a powerful tool for isolating both artifactual and neural EEG sources based on assumptions of temporal independence of spatially overlapping sources. It performed well in correcting the artifacts due to diagonal eye movements in the present paradigm, as indexed by reduction of the electrooculogram amplitude and by visual inspection of the corrected and uncorrected EEG on single epochs and in the averages.

Error saccades were executed faster than correct saccades and, in order to control for contribution of stimulus-related activity to the response-locked ERP averages (Coles et al., 2001), the mean saccadic latency for the correct and incorrect trials was matched by selecting the fastest 25th percentile of the correct trials. This procedure led to the best match for both the mean saccadic latency and the number of trials between the averages for the correct and error saccades.[2] The amplitude of ERP components (except for the ERN) was quantified as the mean voltage in the appropriate time window after the start of saccade relative to mean voltage between 100 and 50 msec in the presaccade baseline. The ERN amplitude was quantified as the peak-to-peak difference between the maximum positive value before the peak (25–65 msec) and the maximum negative value around the peak (65–120 msec). Three separate planned comparisons using two-way repeated measures analyses of variance (ANOVAs), with condition (aware errors vs. correct saccades, unaware errors vs. correct saccades, and aware vs. unaware errors) and electrode site (Fz, Cz, and Pz) as factors, were used to compare the ERP components' amplitudes. Whenever necessary, probability values were adjusted using Geisser–Greenhouse correction for nonsphericity.

RESULTS

Approximately 6.5% of all trials were discarded due to problems with eye position calibration, DC offset correction, and anticipatory (less than 80 msec) or slow (longer than 1000 msec) eye movements. On some trials (<21%), errors were corrected on the fly (redirected saccades), which were included in calculations of mean fixation duration and saccade amplitude. Table 1 con-

Table 1. Mean Performance in the Onset Present and Control (No Onset) Conditions

	Onset Present					*Control*	
		Capture Error		*Misguidance Error*			
	Correct	*Aware*	*Unaware*	*Aware*	*Unaware*	*Correct*	*Misguidance Error*
Scan path (%)	60 (FA = 5%)	10	6	11	8	71 (FA = 6%)	23
Saccade latency (msec)	319	264	276	267	291	317	267
Saccade amplitude (deg)	8.8	8.1	7.9	7.9	7.9	8.7	7.9
Fixation duration (msec)	–	114	38	245	267	–	241
Angular deviation (deg)	6	108	96	103	71	6	92
Confidence rating (1–5)	4.4	4.5	4.1	4.6	4.1	4.4	4.5

Participants reported making an error, but were, in fact, correct (false alarm [FA]) on 5% of the trials in the onset present condition and on 6% of the trials in the control condition.

tains behavioral data for all types of eye movements in this experiment.

Behavioral Results

In the onset distractor present condition, the first saccade went to the color singleton on 60% of the trials. The eyes initially went to the onset distractor on 16% of trials, 10% of these saccades were reported by the participants and 6% of these saccades were not. On 19% of the trials, the eyes initially were misguided elsewhere (i.e., not to the color singleton target or to the onset distractor). Participants reported making an error, but were, in fact, correct (false alarm) on 5% of the trials in the onset present condition and on 6% of the trials in the control condition.

Both aware and unaware onset capture saccades were executed faster than correct saccades [$F(1, 15) = 121.39$, $p < .001$ and $F(1, 15) = 62.09$, $p < .001$, respectively] and were smaller in amplitude [$F(1, 15) = 35.31$, $p < .001$ and $F(1, 15) = 73.36$, $p < .001$, respectively]. Aware onset capture errors were slightly faster than unaware errors [264 vs. 276 msec; $F(1, 15) = 7.82$, $p < .05$] and were similar in amplitude [8.1° vs. 7.9° for the aware and unaware, respectively; $F(1, 15) = 2.17$, $p = .16$]. No post-error slowing (Rabbitt, 1966) relative to the correct trials (322 msec) was found after either aware (320 msec) or unaware (319 msec) onset capture errors.

Fixations on the onset distractor were longer when participants were aware of the error (114 msec) than when they were unaware [38 msec; $F(1, 15) = 21.10$, $p < .001$]. The average angular deviation from the target was greater when participants were aware of the onset capture error [108° vs. 96°; $F(1, 15) = 23.46$, $p < .001$]. Participants were slightly but significantly more confident when they correctly reported the onset capture error than when they failed to notice it [mean confidence rating of 4.5 vs.4.1; $F(1, 15) = 5.75$, $p < .05$].

ERP Results

Saccade-locked ERP grand averages for the aware and unaware onset capture errors, as well as for correct saccades, are shown in Figure 2. Three components differed as a function of whether the eyes were captured by the onset: the ERN (80–120 msec), the Pe (400–500 msec), and the N1 (120–160 msec). The ERN and Pe both had fronto-central topography, whereas the N1 was the largest at the parietal sites. Fronto-central topography is typical for the ERN and not uncommon for the Pe (for an overview, see Overbeek et al., 2005). The N1 was the most pronounced for the aware errors, but was also present when participants executed a correct saccade to the color singleton. A similar component was also found in our previous study using a similar paradigm (Belopolsky & Kramer, 2006). To further isolate the approximate topography of the overlapping ERP components of interest, we created unaware–aware difference waveforms. Their map (Figure 3) illustrates the fronto-central distribution of both the ERN and the Pe. In addition, it shows a narrow parietal distribution (centered around Pz) for the N1 component. It should be noted, however, that there may be other differences between the unaware and aware conditions, and one should be cautious in interpreting the differences in terms of specific ERP components.

Error-related Negativity

Separate planned comparisons using two-way repeated measures ANOVAs showed that, for both the aware and unaware onset capture errors, the ERN was larger than for the correct responses [$F(1, 15) = 8.29$, $p < .05$ and $F(1, 15) = 12.39$, $p < .005$, respectively]. Importantly, the ERN was larger for the unaware than for the aware errors [$F(1, 15) = 6.20$, $p < .05$].

Although for both types of errors the ERN amplitude appeared to be the greatest at the Fz electrode, reduced at the Cz electrode and the smallest at the Pz electrode, it did not have a significantly different distribution across the electrode sites [$F(2, 30) = 2.44$, $p = .1$ and $F(2, 30) = 0.39$, $p = .68$, for the aware and unaware capture errors, respectively]. The difference between the ERN for the aware errors and unaware errors seemed to be more pronounced frontally and decreased at the central and posterior sites, however, this was only marginally significant [$F(2, 30) = 2.60$, $p < .09$].

N1

Separate planned comparisons using two-way repeated measures ANOVAs showed that that the N1 amplitude was different between correct eye movements and the aware capture errors [$F(1, 15) = 7.01$, $p < .05$] and was marginally different from the unaware [$F(1, 15) = 3.97$, $p = .07$] capture errors.[3] The N1 for the aware onset distractor capture errors was not significantly greater than for the unaware distractor onset capture errors [$F(1, 15) = 2.10$, $p = .17$].

The N1 for both aware [$F(2, 30) = 16.24$, $p < .001$] and unaware capture errors [$F(2, 30) = 5.97$, $p < .05$] also had a different distribution across the electrode sites. For both types of errors, the amplitude appeared to be the greatest at Pz, decreased at Cz, and virtually absent at Fz. Although there was no overall difference between the aware and unaware errors, the N1 appeared much larger for the aware errors than for unaware errors, which seemed to be the most pronounced at the parietal site [$F(2, 30) = 7.97$, $p < .01$]. Post hoc comparisons showed that the difference in the N1 amplitude between aware and unaware errors was significant at Pz [$F(1, 15) = 6.85$, $p < .05$], but did not reach significance for Fz and Cz (both $Fs < 1$).

The N1 component seemed to be related to the online adjustment of the oculomotor program. It was

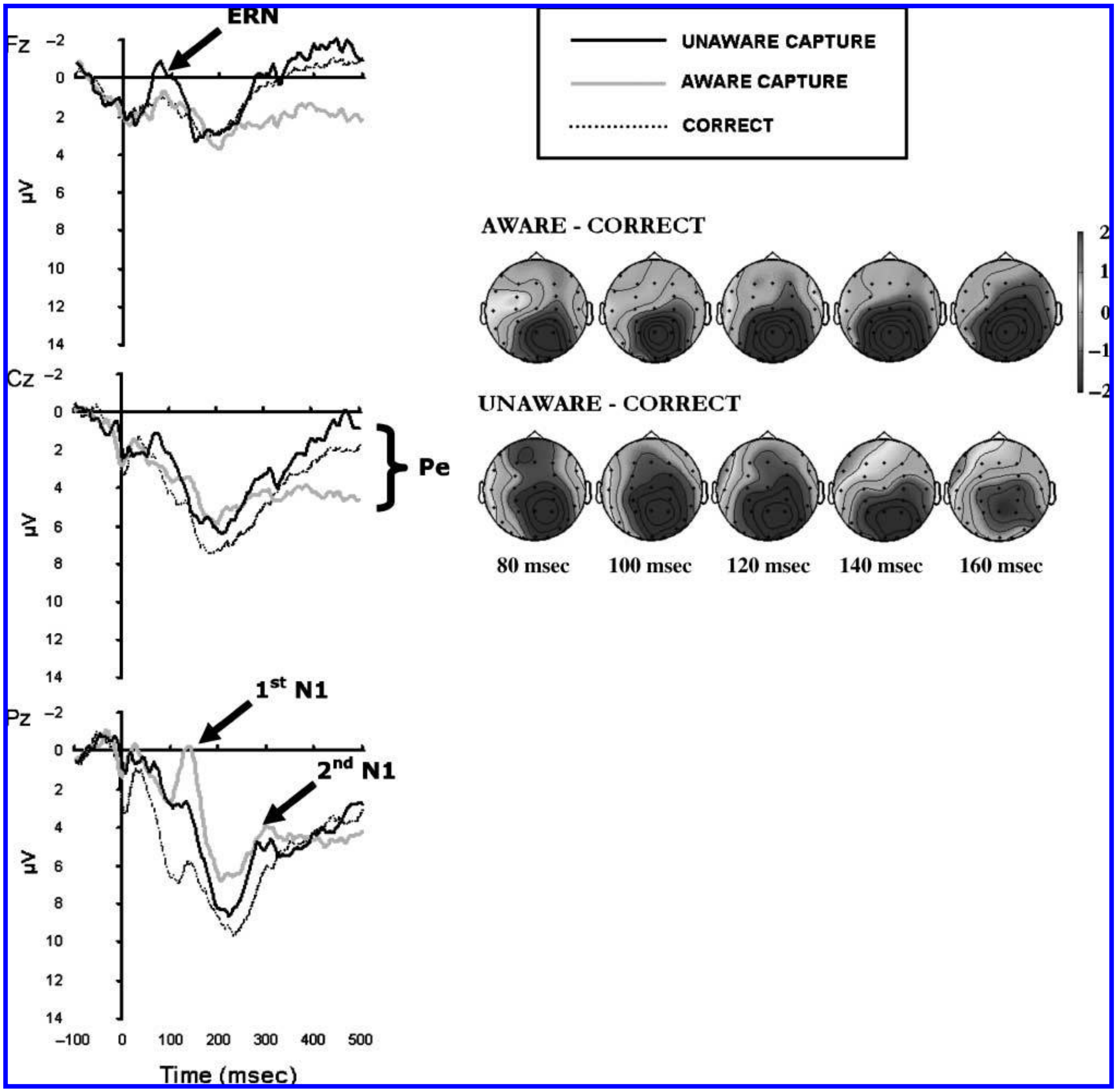

Figure 2. Grand-average saccade-locked ERP waveforms for correct saccades, aware and unaware onset capture errors (left). Voltage maps for difference waveforms (error minus correct) for the aware and unaware capture errors (right).

narrowly focused over the parietal sites (Figure 3) and had a similar time course for both correct and erroneous eye movements. Its amplitude was the smallest for the correct saccades and the unaware errors, for which the on-line adjustment was presumably minimal. The on-line adjustment of the oculomotor program was presumably greater for the aware capture errors because the programming of the corrective saccade was not completed before the saccade was initiated (Godijn & Theeuwes, 2002). If the N1 component is related to the on-line adjustment of the oculomotor program, we should also be able to see it in response to the second (corrective) saccade to the target. We did not have enough trials to create averages time-locked to the second saccade, but even in the present waveforms, there was a hint of a second N1 component beginning around 250 msec and peaking around 300 msec. Importantly, it was only present for the capture errors and was absent for the correct eye movements. To confirm this observation, we quantified the amplitude as a mean within 250–320 msec at Pz. It showed that this component was larger for the aware [$F(1, 15) = 4.67, p < .05$] and was marginally larger for the unaware [$F(1, 15) = 3.22, p = .09$] capture errors than for the correct saccades. There was no

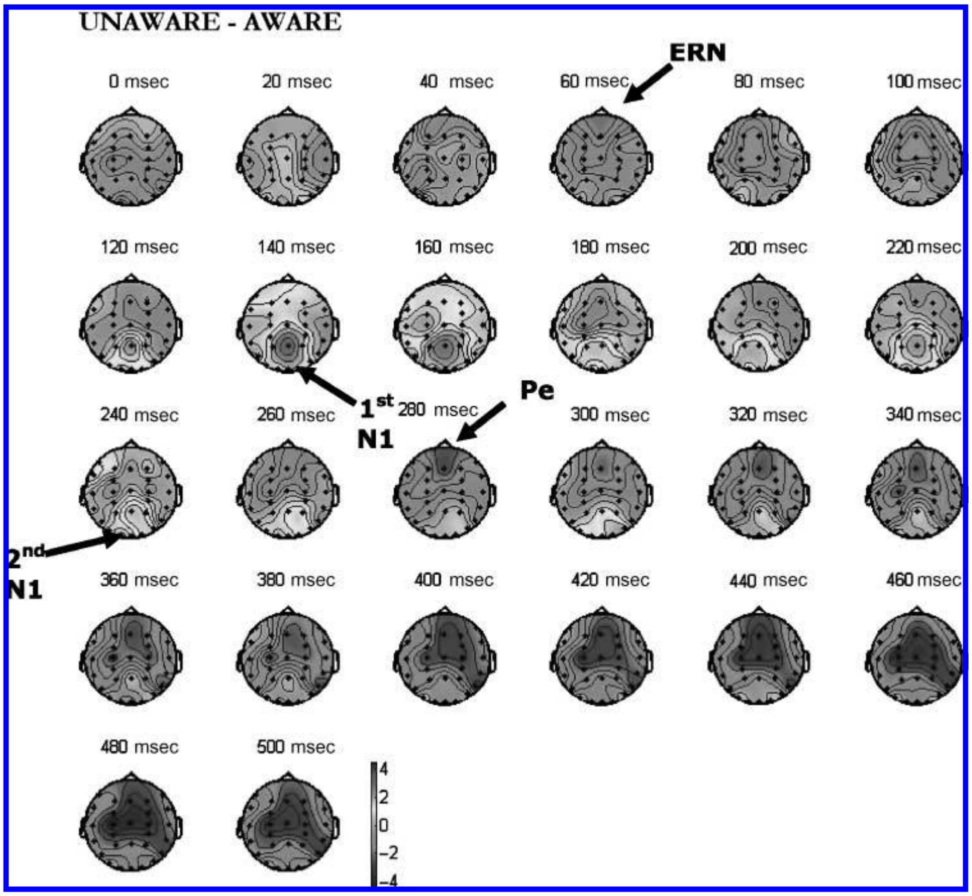

Figure 3. Voltage maps for difference waveforms for the unaware versus aware capture errors. Note that due to subtraction the polarity of the N1 and the Pe is reversed. The component labels give an approximate indication of the ERP components in space and time.

difference in amplitude between the aware and unaware capture errors ($F < 1$).

Error-related Positivity (Pe)

In addition to the ERN and N1, the Pe was observed starting around 300 msec after a saccade at the frontal and central electrode sites for the trials on which participants reported making an error. Separate planned comparisons using two-way repeated measures ANOVA showed that for the aware onset capture errors, the Pe was larger than for the correct responses [$F(1, 15) = 5.40$, $p < .05$]. However, the Pe was not different between the unaware onset capture errors and the correct responses [$F(1, 15) = 1.50$, $p = .24$]. Importantly, the difference between the aware and unaware errors was significant [$F(1, 15) = 7.01$, $p < .05$].

The Pe for the aware [$F(2, 30) = 1.69$, $p = .21$], as well as for the unaware capture errors [$F(2, 30) = 1.48$, $p = .25$] had a similar distribution across the electrode sites. However, the difference between the aware and unaware errors appeared to be larger at the frontal and central sites [$F(2, 30) = 4.65$, $p < .05$]. Post hoc comparisons confirmed that the difference in the Pe amplitude between aware and unaware errors was significant at Fz [$F(1, 15) = 8.42$, $p < .01$] and Cz [$F(1, 15) = 8.42$, $p < .01$], but not at Pz ($F < 1$).

Additional Analysis: Misguidance Errors

To verify the generality of the effects found for the onset distractor capture errors, we also analyzed ERPs for the misguidance errors—the trials on which participants first made an eye movement to a nontarget (but not the onset distractor)—in both experimental and control (no-onset) conditions (Figure 4).

In the experimental condition, we were also able to separate the trials based on the awareness of making a misguidance error. Two of the participants had to be excluded because they did not make enough aware misguidance errors (<2%). The similar pattern of ERP components was clearly evident (Figure 4A). Both the ERN for aware [$F(1, 13) = 7.13$, $p < .05$] and for unaware misguidance errors [$F(1, 13) = 5.74$, $p < .05$] was significantly different from the correct saccades. However, the aware and unaware misguidance elicited the ERN of similar amplitude ($F < 1$). The N1 was marginally larger for the aware misguidance errors than

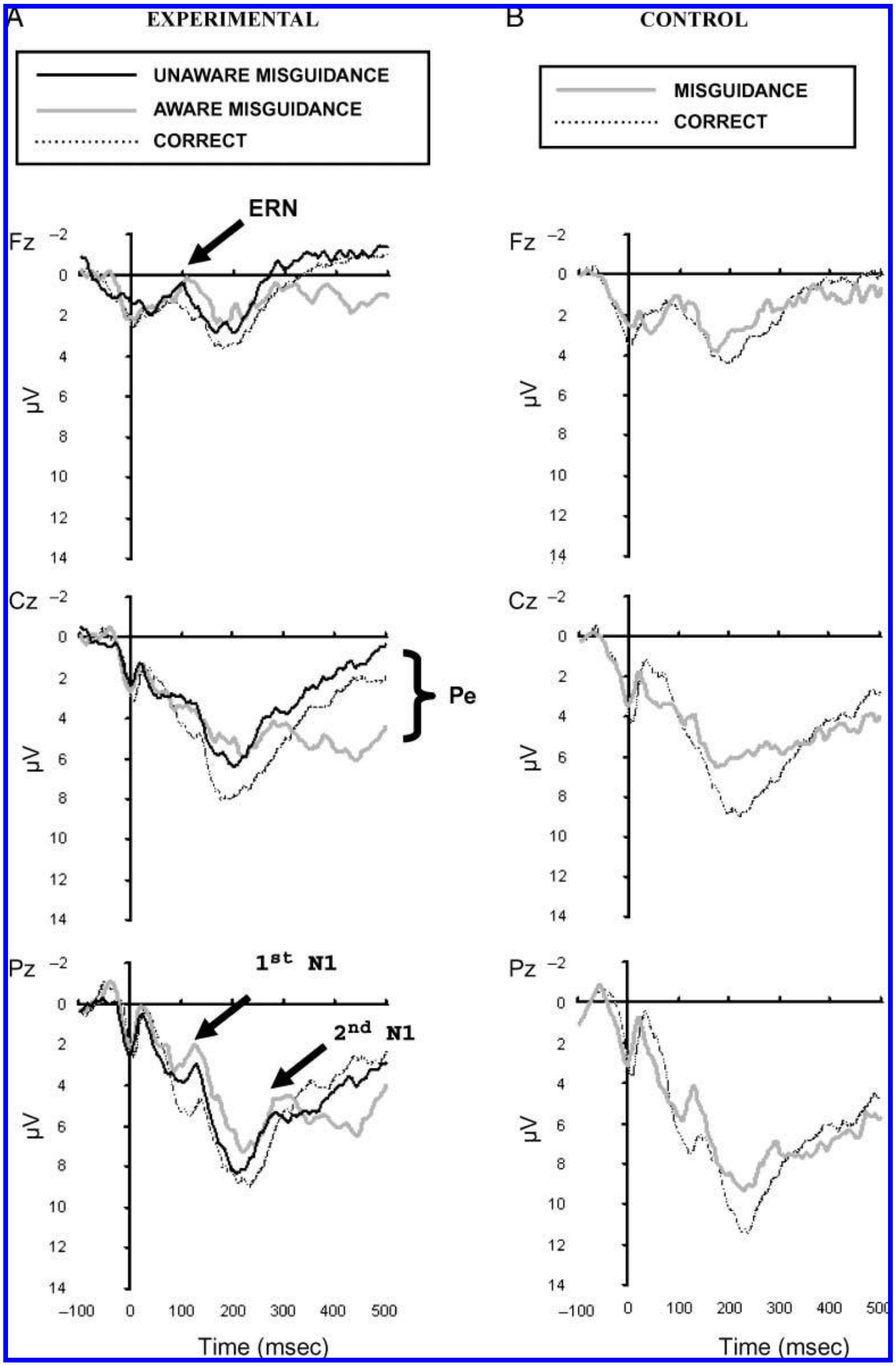

Figure 4. (A) Grand-average saccade-locked ERP waveforms for correct saccades, aware and unaware misguidance errors in the experimental (onset present) condition. (B) Grand-average saccade-locked ERP waveforms for correct saccades and misguidance errors in the control (no onset) condition.

for the correct saccades [$F(1, 13) = 3.85$, $p = .07$] and for the unaware errors was significantly larger than for the correct saccades [$F(1, 13) = 6.31$, $p < .05$]. The N1 appeared to be slightly larger for the aware misguidance errors than for unaware errors, but this difference was not significant [$F(1, 13) = 1.12$, $p = .31$]. The Pe was also present when participants were aware of making a misguidance error [$F(1, 13) = 6.12$, $p < .05$], but not when they were unaware ($F < 1$). The Pe was marginally larger for the aware misguidance errors than for unaware misguidance errors [$F(1, 13) = 4.02, p = .07$].

In the control condition, where no onset was presented, we compared the misguidance errors to the correctly executed saccade. We observed a nonsignificant trend for the ERN and N1, but not for the Pe, because there were not enough trials to separate based on the awareness judgment (Figure 4B).

Overall, misguidance errors elicited very similar components as the oculomotor capture errors, despite the different time course of these eye movements (misguidance eye movements had much longer fixation durations) and the presence of the onset distractor. Importantly, there was also a trend for the second N1 component with a time course that was similar to the onset capture errors. These findings open a possibility for speculation that adjustment of the oculomotor program begins before the eyes leave the erroneously fixated object.

Correlational Analysis

Based on the previous studies, we predicted a certain relationship between the ERP components of interest and some of the performance measures. More specifically, we hypothesized that the ERN should be related to the magnitude of error, N1 should be related to the fixation duration on the onset distractor, and the Pe should be related to the confidence measures of awareness. The correlations between the amplitude of the components (ERN at Fz, N1 at Pz, and Pe at Cz) for aware and unaware onset capture errors and the performance measures are presented in Table 2.

As predicted, the ERN increased with the angular error, it was marginally significant for the aware capture errors ($r = -.43, p = .09$) but not for the unaware errors ($r = -.02$, $p = .96$). Interestingly, the ERN was not related to the saccade amplitude (aware errors: $r = -.19$, $p = .48$; unaware errors: $r = .26, p = .33$), suggesting that direction of the first eye movement was the main factor in determining the degree of deviation from correct performance.

The N1 amplitude increased with the duration of fixation at the onset for the aware ($r = -.59, p < .05$), but not for the unaware capture errors ($r = -.01, p = .96$). This suggests that longer fixations on the onset distractor during oculomotor capture might be accompanied by additional adjustments of oculomotor program.

We also found that the Pe amplitude was positively correlated with the confidence measures for the aware capture errors ($r = 0.66$, $p < .01$), but not for the unaware errors ($r = -.16, p = .57$). The finding that more confidence about being aware of making an error is linked to Pe amplitude (measured well before the confidence rating is taken) is consistent with previous studies connecting Pe to the conscious processing of errors. Importantly, none of the components were significantly correlated with other performance measures.

DISCUSSION

The present findings show that awareness plays an important role in processing of oculomotor capture. Unlike the antisaccade paradigm, in the oculomotor capture paradigm, there is no need to attend to the onset because it is completely irrelevant to the task that participants need to perform. This allowed us to observe several important differences between the aware and unaware capture errors.

First, participants were more likely to report an initial misdirection of the eyes to the task-irrelevant onset (10%) than fail to report it (6%). Second, the confidence rating for the unaware errors was high, but was lower than for the aware errors. These findings suggest that participants were conservative in deciding if their response was correct and only a few errors went unnoticed. Third, the onset fixation durations were shorter for the unaware errors (38 msec) than for the aware onset capture errors (114 msec) and were well under 100 msec, which is similar to the typically found fixation

Table 2. Correlations between Component Amplitudes and Behavioral Performance

	ERN		*N1*		*Pe*	
	Aware Onset Capture Error	*Unaware Onset Capture Error*	*Aware Onset Capture Error*	*Unaware Onset Capture Error*	*Aware Onset Capture Error*	*Unaware Onset Capture Error*
Angular deviation (deg)	−0.43*	−0.02	0.31	0.16	0.28	0.23
Saccade amplitude (deg)	−0.19	0.26	−0.09	0.10	0.17	0.47*
Fixation duration (msec)	−0.35	−0.09	−0.59**	−0.01	0.31	−0.18
Confidence rating (1–5)	−0.33	−0.15	−0.02	0.18	0.66***	−0.16

*Marginally significant at $p = .09$.

**Significant at $p < .05$.

***Significant at $p < .01$.

durations in the oculomotor capture paradigm (Godijn & Theeuwes, 2002), as well as for unaware errors in some of the antisaccade tasks (Mokler & Fischer, 1999). Fourth, the magnitude of angular error from the target was greater for the aware than for the unaware capture errors, but there was no difference in amplitude of the saccade between the two types of errors. Because there were several target locations and the onset distractor location varied from trial to trial, the magnitude of the angular deviation from the path to the target seemed to be the determining factor in realizing that an error has occurred. Taken together, these performance characteristics suggest that, in our study, the unaware capture errors were quite different from the aware capture errors.

While carefully controlling for selection of the unaware errors, we observed the following main results: (1) The ERN was smaller for aware than for unaware capture errors, but was similar for aware and unaware misguidance errors; (2) The N1 was larger for aware than for unaware capture errors, but was similar between aware and unaware misguidance errors; (3) The Pe was present only when participants were aware of making an error. Below we discuss these results in relation to how awareness affects the processes of error detection and correction and what processes might be involved in becoming aware of oculomotor capture errors.

Detection and Correction of Oculomotor Capture Errors

The present study showed that both aware and unaware oculomotor capture errors elicit an ERN, which was larger for the unaware capture errors. However, no difference between the amplitude of the aware and unaware errors was found for the misguidance errors. Although the latter results are consistent with the previous findings (O'Connell et al., 2007; Endrass et al., 2005; Nieuwenhuis et al., 2001), the former results are not. If, as suggested in the previous studies, the ERN represents the process of unconscious error detection, it should not be modulated by awareness. How can this discrepancy be explained?

Note that oculomotor errors can be corrected without awareness (see also Kramer, Hahn, Irwin, & Theeuwes, 2000; Theeuwes et al., 1998, 1999). Successful correction of oculomotor capture errors on every trial can be explained by the competitive integration model of saccade generation (Godijn & Theeuwes, 2002). According to this model, exogenous and endogenous inputs are integrated on a common saccade map. Oculomotor capture occurs when an exogenous (incorrect) saccade is programmed faster than an endogenous (correct) saccade. However, erroneous saccades can be corrected on the fly or with a very brief fixation duration when the programming of the endogenous saccade is accomplished. As a result, these erroneous saccades often can be corrected with no subjective awareness.

We propose that the ERN is not modulated by awareness per se, but is modulated by proximity in time between the programming of the correct and erroneous responses, with the greater temporal overlap leading to increased ERN amplitude. The unaware capture errors were corrected much faster than the aware capture errors, suggesting that the correct eye movement program was largely completed before the eyes started to move.[4] Greater overlap in the two programs led to the larger ERN for the unaware capture errors. In contrast, both aware and unaware misguidance errors were corrected slowly (around 250 msec), hence, a comparable temporal overlap between the correct and erroneous motor programs and the ERN of a similar magnitude.

A similar result has been obtained by Rodriguez-Fornells, Kurzbuch, and Munte (2002), who showed that the ERN was greater for the errors followed by fast than slow manual corrections. They demonstrated that the error correction processes were initiated before or in parallel with the appearance of the ERN. For fast corrections, the larger clash between correct and erroneous button-press responses led to a larger ERN. Importantly, in the study by Nieuwenhuis et al. (2001), the unreported erroneous saccades were also followed by a rather long correction time (200 msec, comparing to 95 msec in the original study of antisaccade error awareness by Mokler & Fischer, 1999). A trend for the ERN to be larger for the unaware errors than for the aware errors can also be seen in the previous studies (Endrass et al., 2005; Nieuwenhuis et al., 2001).

The finding of a larger ERN for unaware (fast corrected) than aware (slow corrected) erroneous saccades can be accommodated by several existing accounts of the ERN. If the ERN reflects monitoring of a response conflict, then coactivation of the correct and error motor programs would be higher for the fast corrections than for the slow corrections. Alternatively, if the ERN reflects a mismatch between the representations of the correct and actual response, the mismatch would be greater for the fast corrections because the representation of the correct response (target location) is already acquired, whereas for the slow corrections the representation of the correct response might be too impoverished for the proper matching (Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996). Interestingly, the ERN was also marginally correlated with the magnitude of the angular error for the aware capture errors. The fact that there was a trend for the ERN to increase as the angular error from the target increased, is consistent with previous studies claiming that the ERN reflects the amount of conflict between the correct and erroneous response (van Veen & Carter, 2002) or a mismatch signal (Holroyd & Coles, 2002; Coles et al., 2001; Bernstein et al., 1995).

In addition to the ERN, we also observed a posterior N1 component whose distribution (strongly focused at Pz) suggests that it reflects corrective mechanisms of the posterior error system. A similar component was recently reported in relation to manual tracking errors (Krigolson & Holroyd, 2006). For the onset capture errors, the N1 was the largest when participants reported being aware of making an error of moving their eyes to the onset distractor. However, awareness of making an erroneous eye movement would be too slow to affect on-line error correction (Desmurget & Grafton, 2000). Note that even the aware saccades were corrected faster (114 msec) than would have been expected if participants programmed an intentional (conscious) corrective eye movement (approximately 250–300 msec). As suggested earlier, the longer fixation duration for the aware errors was probably due to an increased delay in completion of the correct eye movement program (Godijn & Theeuwes, 2002). This would suggest a greater involvement of the posterior error system. Basically, it means that for the aware errors a spatial representation of the target was not sufficiently derived based on visual information obtained prior to saccade. Therefore, a rechecking of the target location and tuning of the saccade program was needed after the saccade was launched, resulting in the longer fixation duration. Presumably, for the unaware errors such rechecking was not required (hence, a very short fixation) and the spatial representation of the target derived before the saccade was launched was sufficient to program the saccade to the target.

Importantly, the fixation duration for the aware capture errors was correlated with the N1 amplitude, that is, the longer fixation durations corresponded to a larger N1 and greater necessity for on-line adjustment of the eye movement program. Corroborating this argument is the finding that the N1 amplitude was similar for the aware and unaware misguidance errors, which had similar overlap in programming of the correct and erroneous saccades. An interesting observation was that for the onset capture and misguidance errors, but not for the correct saccades, there was what appears to be a second N1 component, possibly reflecting on-line tuning of the saccade program to the target (for similar results, see Belopolsky & Kramer, 2006). The similar time course of this component for all erroneous saccades with different fixation durations allows us to speculate that the N1 reflects on-line adjustment of an oculomotor program that can occur before fixation has ended. The N1 observed in this study might be a useful tool to further investigate on-line adjustments of saccadic programs by the posterior error processing system.

In line with some recent findings (Belopolsky & Kramer, 2006; Krigolson & Holroyd, 2006), our results provide strong evidence for both anterior (the ERN) and posterior (the N1) error system involvement in tasks requiring on-line error correction that can occur without awareness. As recently proposed by Krigolson and Holroyd (2006), the role of the anterior error system is to assess high-level errors (such as goal attainment), whereas the role of the posterior error system is on-line evaluation and correction of low-level errors (such as trajectory deviations). Consistent with previous research (Nieuwenhuis et al., 2001; Desmurget & Grafton, 2000), we find that both anterior and posterior error systems are not directly modulated by awareness of making an error. Subjective awareness of an error appears to be a product of some other computational mechanisms.

Conscious Recognition of Oculomotor Capture Errors

In contrast to the ERN and consistent with the previous findings (O'Connell et al., 2007; Endrass et al., 2005; Nieuwenhuis et al., 2001), the Pe was elicited when participants were aware of committing an error. This was the case for both the capture and misguidance errors. Importantly, no error positivity was present on the unaware trials (Pe was not different from the correct saccades), suggesting that there was most likely no partial awareness on these trials (in contrast to Nieuwenhuis et al., 2001). This finding confirms that the Pe represents a separate mechanism of error processing, primarily dealing with conscious error recognition and evaluation (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Falkenstein et al., 1991). Because there was no post-error slowing in this experiment, it does not seem that the Pe is related to or represents a system of error compensation and remedial action (see also Fiehler, Ullsperger, & Von Cramon, 2005; Overbeek et al., 2005).

Additional and novel evidence regarding the significance of the error positivity is provided by the fact that the Pe amplitude was found to increase for the participants who reported being more confident in their awareness ratings. The fact that unlike other components the Pe was not correlated with any particular eye movement performance parameter may suggest that the Pe reflects not a simple recognition that an error had occurred, but a complex evaluation and integration of several performance parameters that lead to awareness. The more performance parameters (such as angular error, fixation duration, saccade amplitude, etc.) deviate from what is expected under the correct response, the larger the Pe amplitude and confidence of being aware of making an error. Such integrative supervisory system would be very sensitive in detecting even very quickly corrected oculomotor errors, such as the aware capture errors in the present study (Johnson et al., 2002).

Conclusion

In the present study, we took special care in separating the unaware errors from the aware errors. Our results show that the early processes of error detection and correction (as represented by the ERN and the N1) are not directly affected by subjective awareness of making an error. Instead, they seem to represent the degree of temporal overlap between the programming of the correct and erroneous response. We found that only a later component (the Pe) is modulated by awareness of making an erroneous eye movement. We speculate that the Pe represents an outcome of computation of cumulative deviation from the expected response based on integration of several performance parameters derived mostly through peripheral feedback. This explains why the Pe displays substantial variability between participants and tasks, perhaps because not all studies explicitly require monitoring of peripheral feedback. We propose that awareness of oculomotor capture primarily depends on this later process.

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Notes

1. Two different arrangements of stimuli were used in order to have the same locations for the onset distractor capture trials and the correct trials to control for differential contribution of eye movement artifacts to the EEG recorded on these trials.
2. After the matching procedure, the mean saccade latency for the subset of correct saccades was 268 msec (20% of trials) in the experimental condition and 271 msec (27% of trials) in the control condition.
3. The N1 amplitude was also reanalyzed using the peak-to-peak measure, which yielded very similar results. The N1 amplitude was different between correct eye movements and the aware [$F(1, 15) = 7.09, p < .05$] capture errors and not significantly different from the unaware [$F(1, 15) < 1$] capture errors. The N1 for the aware onset distractor capture errors was marginally greater than for the unaware distractor onset capture errors [$F(1, 15) = 3.89, p = .07$]. The N1 appeared much larger for the aware errors than for the unaware errors, which seemed to be the most pronounced at the parietal site [$F(2, 30) = 4.23, p < .05$]. Post hoc comparisons showed that the difference in the N1 amplitude between aware and unaware errors was significant at Pz [$F(1, 15) = 6.63, p < .05$], but did not reach significance for Fz and Cz [$F(1, 15) = 2.41, p = .14$ and $F < 1$, respectively].
4. Consistent with this argument is the observation that the unaware capture errors had a slightly, but significantly, slower saccade latency than the aware capture errors (264 vs. 276 msec for the aware and unaware capture errors, respectively).

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