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Research Report
Error-processing of oculomotor capture
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ABSTRACT

Previous research has shown that salient events have a powerful effect on our covert (attentional capture) and overt (oculomotor capture) behavior. The goal of the present study was to examine whether oculomotor capture errors, which are purely stimulus-driven, meaning that they are not in any way defined by the task-set, elicit the error-related negativity (ERN). Using a hybrid of antisaccade and oculomotor capture tasks, we showed that erroneous prosaccades and irrelevant onset capture errors elicited the ERN of similar amplitude. The results suggest that participants adopted an internal standard for a direct eye movement to the target (optimal performance) and any eye movement that deviated from this path was detected by a performance-monitoring system and indexed by the error-related negativity.

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1. Introduction

A major research question in visual attention is the relationship between goal-directed and stimulus-driven control of selection at different stages of information processing. Attention is said to be goal-directed or under top-down control when information is selected according to observers' goals or intentions. When attention is allocated based on the properties of incoming information and irrespectively of the observers' goals, it is said to be stimulus-driven or under bottom-up control. Stimulus-driven attention plays an important role of a "circuit-breaker", allowing detection of salient events, which often signal critical changes in the environment and would otherwise go unnoticed.

A number of studies have demonstrated that salient events can override top-down settings and capture attention in a stimulus-driven fashion (Yantis and Jonides, 1984). For example, Theeuwes et al. (1998, 1999) demonstrated that an onset of a salient, but task-irrelevant new object triggers not only a covert attentional shift (attentional capture), but also an erroneous

saccade to its location (oculomotor capture). Although the onset was completely irrelevant to the task (i.e. it never served as the target and no responses were associated with it), oculomotor capture occurred on 30–40% of the trials. The onset fixations were very brief (less than a 100 ms) and then the eyes were quickly redirected to the correct target location. This quick online correction suggests that at least some of the programming of an exogenous saccade to the onset and an endogenous saccade to the target likely occurred concurrently.

Since oculomotor capture represents a temporary disruption of efficient task performance (saccade goal is still achieved on every trial), it could be viewed as an error. Detection and correction of response errors have been one of the central research questions in the area of performance monitoring (Rabbitt, 1966). Several electrophysiological markers related to error-processing have been identified. The error-related negativity (ERN or Ne) – a negative deflection in the event-related brain potential (ERP) – is observed about 100 ms after the incorrect response is executed (Falkenstein et al., 1991, 2000; Gehring et al., 1993). It typically has maximal

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amplitude over the frontal and central electrode sites and is often, but not always, followed by a slow positive wave with a centro-parietal distribution, termed the error positivity or Pe. The Pe is thought to be related to conscious error compensation and remedial action (Falkenstein et al., 1991, 2000; Nieuwenhuis et al., 2001).

Currently, there are two main competing theories concerning the functional significance of the ERN. According to the error-detection theory (Coles et al., 2001; see also Holroyd and Coles, 2002), the ERN represents a mismatch signal resulting from comparison of the “efferent copy” of an executed response to the representation of the correct response. On the contrary, the conflict monitoring theory postulates that errors are not special, and the ERN represents an outcome of a more general process of detection of a conflict between simultaneously present responses, which is a function of the evaluative monitoring process (Botvinick et al., 1999; Carter et al., 1998; van Veen and Carter, 2002).

An interesting research question is whether oculomotor capture errors, which are purely stimulus-driven, meaning that they are not in any way defined by the task-set, elicit the ERN. In all tasks typically used to study performance monitoring, errors are clearly defined by the task instructions: responding with a wrong key in the choice reaction time tasks (Gehring et al., 1993), failures to withhold a response on the no-go trials (Scheffers et al., 1996; Van 't Ent and Apkarian, 1999) in the go-no and stop tasks or missing an external RT deadline (Luu et al., 2000). In the oculomotor capture task, the onset distractor does not have any stimulus–response mappings associated with it and therefore, error responses are not explicitly defined by the task instructions. Since the onset is irrelevant to the task (and predicts neither the location nor the identity of the target), it does not need to be attended or processed in order to successfully complete the task. The saccade goal is achieved on every trial, despite the deviations from an optimal response execution (i.e. a direct path) that also often escape conscious awareness (Theeuwes et al., 1998). With other tasks, especially using manual responses, it is rather difficult to examine whether such deviations caused by a task-irrelevant event are detected by a performance-monitoring system. In manual response tasks, all responses are typically defined by the task and it is difficult to come up with a task-irrelevant event that would consistently trigger a deviation from a correct response.

In a recent study, it was demonstrated that the ERN is elicited by prosaccade errors in the antisaccade task independently of subjective awareness of error (Nieuwenhuis et al., 2001). However, in the antisaccade task, the error responses are also defined by the task instructions: on every trial, there is an explicit instruction not to look at the cue, simply because the task is to look away from the cue. The onset cue and its location are critically relevant to the task and in order to do the task, it is essential not only for the cue to be present, but also for it to be attended. In the oculomotor capture task, the errors are truly stimulus-driven, since neither the presence nor the location of the onset is relevant to the task, predict anything about the target and the onset does not have to be attended in order to perform the task (Theeuwes et al., 1998, 1999).

In the present study, our goal was to examine whether deviations from optimal performance caused by the presence

of a task-irrelevant onset elicit the ERN. If participants adopt an internal standard for a direct eye movement to the target, then any eye movement that deviates from this path should elicit the ERN. If, however, no such internal standard is set, no ERN should be observed. To have a baseline for the ERN measurement, we combined two paradigms that are commonly used to study control of overt visual attention: an antisaccade task and oculomotor capture task (Fig. 1). The antisaccade part of the task was different from a typical antisaccade task, since participants needed to execute a saccade away from a color singleton, not an onset cue. Despite these differences, we expected to replicate previous findings using antisaccade task (Nieuwenhuis et al., 2001) and observe the ERN for the prosaccade errors. On some proportion of trials, a new distractor circle appeared at the same time the color singleton was revealed. This hybrid design enabled the comparison of the prosaccade, onset distractor capture errors (when the eyes first go to the onset distractor before going to the uniquely colored target) and other misguided (first going in the direction of another distractor) eye movements within the same task and within subjects. The question that we address here is whether these three types of disruptions of task-defined eye movement performance are treated similarly by the error monitoring system that is reflected by the ERN.

2. Results

2.1. Discarded data

Trials, on which the eye calibration was lost, as well as the trials with saccadic latency shorter than 80 ms (anticipatory eye movements) or longer than 1000 ms were discarded. Trials containing DC offset correction were also excluded from the analysis. Approximately 6% of all trials were discarded and not further analyzed.

2.2. Eye movement performance

Eye movement data are shown in Table 1. On some trials, eye movement errors were corrected on the fly (redirected saccades). Since there was no fixation on these trials, they were not included in the calculations of the mean fixation duration and saccade size (<31% of the total number of errors).

When asked after the completion of the experiment, all the participants reported the appearance of the onset distractor, but significantly underestimated the number of onset capture and prosaccade errors (“I moved my eyes there on one or two trials”). The presence of the task-irrelevant onset had an effect on the saccade direction, with fewer saccades (43% vs. 51%) going in the direction of the antisaccade target ($F(1,8) = 12.48$, $P < 0.01$), but it had no effect on the number of prosaccade errors (25%; $F(1,8) = 0.39$, $P = 0.86$).

As expected, erroneous eye movements (364 ms) were executed faster than correct antisaccades (433 ms; $F(1,8) = 48.73$, $P < 0.001$). Erroneous saccades were also different from each other in latency ($F(2,16) = 4.72$, $P < 0.05$). Post hoc comparisons showed no reliable difference in the saccade

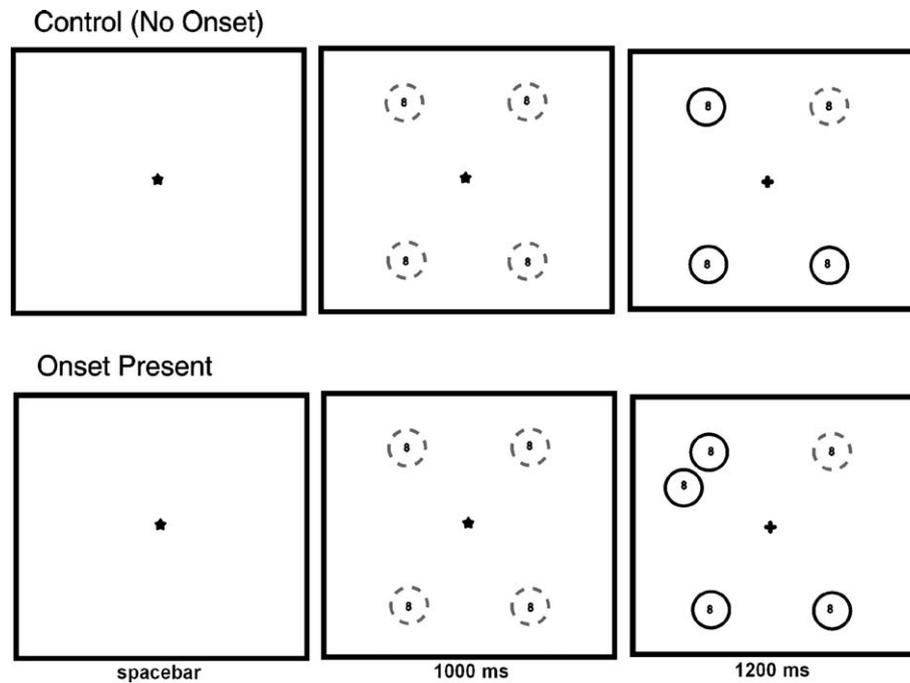


Fig. 1 – Schematic illustration of stimuli and time-course of events in the task. Dashed lines represent the gray and solid lines represent the red color.

latencies between onset capture and prosaccade errors (361 and 347 ms; $F(1,8) = 1.29, P = 0.29$) or between onset capture and misguidance errors (361 and 386 ms; $F(1,8) = 3.02, P = 0.12$). However, prosaccade errors were faster than misguidance errors (347 and 386 ms; $F(1,8) = 10.78, P < 0.02$). It appears that prosaccade errors were slightly more impulsive than misguidance errors.

Erroneous eye movements (7.4°) were shorter than correct antisaccades (8.6° ; $F(1,8) = 58.88, P < 0.001$). Erroneous saccades differed in amplitude from each other ($F(2,16) = 18.87, P < 0.001$). Post hoc comparisons showed no reliable difference in the saccade amplitude between onset capture and prosaccade errors (7.1° vs. 7.0° ; $F(1,8) = 0.59, P = 0.47$). Both onset

capture and prosaccade errors were shorter than misguided saccades ($F(1,8) = 23.06, P < 0.001$ and $F(1,8) = 32.30, P < 0.001$, respectively), again suggesting that misguidance saccades might be less impulsive and more strategic.

2.3. Electrophysiological data

The saccade-locked ERPs elicited in the onset present condition are presented in Fig. 2A. From this figure, it is evident that on trials when participants did not move their eyes directly to the antisaccade target a negative deflection starting around 75 ms and peaking around 110 ms post-saccade was observed. Its amplitude appeared to be greater

Table 1 – Number of trials, saccadic reaction time (SRT), amplitude and fixation duration for eye movements in the onset present and control (no onset) conditions

	Onset present				Control		
	Correct antisaccade	Prosaccade error	Onset capture error	Misguidance error	Correct antisaccade	Prosaccade error	Misguidance error
Trials (%)							
Mean	43%	25%	11%	21%	51%	24.5%	24.5%
SD	(15)	(10)	(7)	(11)	(15)	(14)	(12)
SRT (ms)							
Mean	433	347	361	386	428	354	390
SD	(59)	(36)	(37)	(45)	(50)	(38)	(34)
Amplitude (degree)							
Mean	8.6	7.0	7.1	8.0	8.8	6.9	8.5
SD	(0.9)	(1.1)	(1.1)	(0.9)	(0.6)	(1.2)	(0.9)
Fixation (ms)							
Mean	–	46	58	65	–	52	62
SD		(19)	(26)	(48)		(18)	(39)

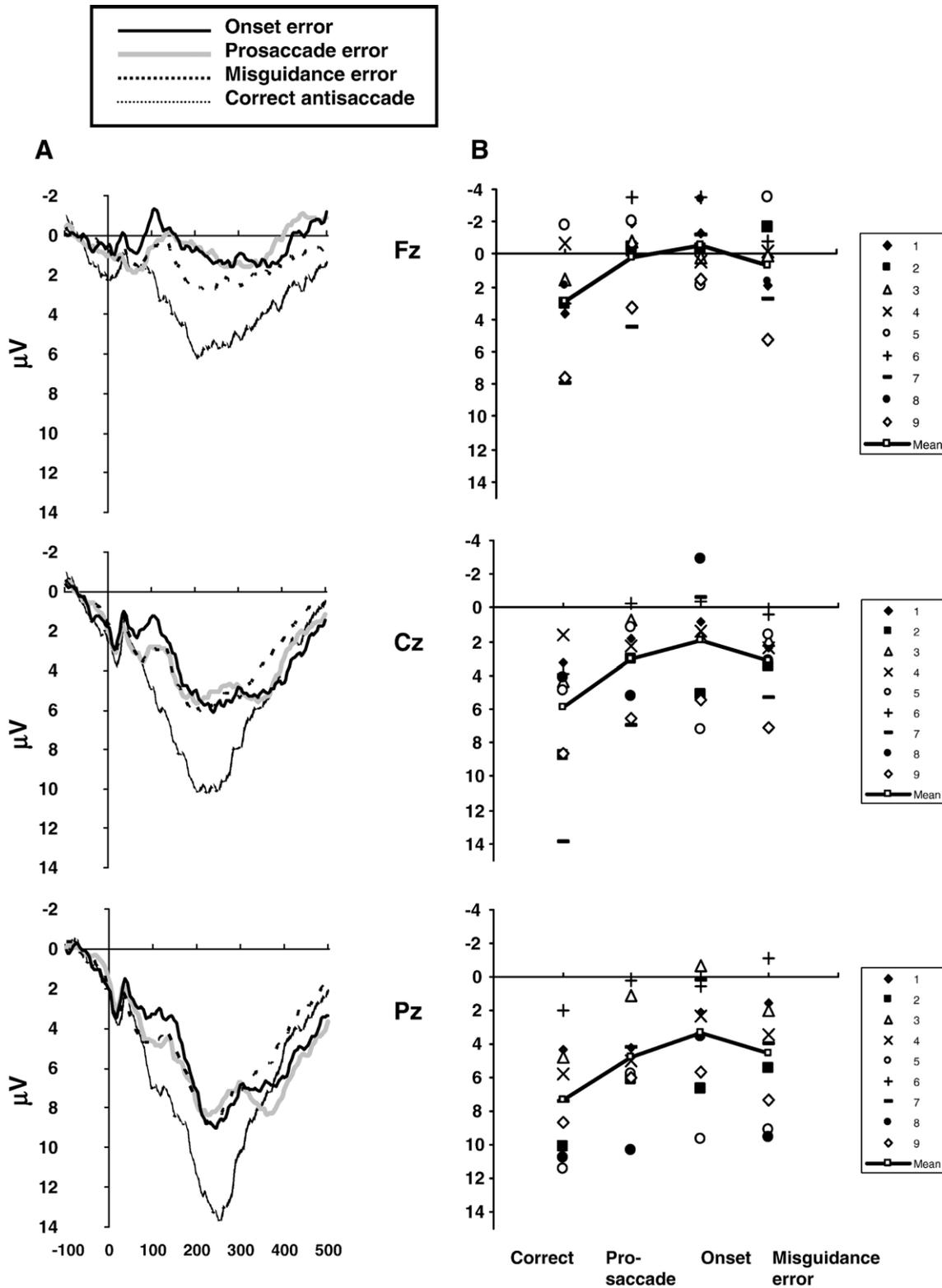


Fig. 2 – (A) Grand-average saccade-locked ERP waveforms for correct antisaccades, prosaccade errors, onset capture errors and misguidance errors. (B) Mean ERN amplitudes for each participant for each eye movement type. The separate symbols represent the different participants in the study.

at the frontal and central midline sites, and it was absent on trials when subjects executed a correct antisaccade (see Fig. 3 for a topographical map for each of the error types). Based

on these features, we can conclude that the observed negative component is indeed the ERN (Gehring et al., 1993; Nieuwenhuis et al., 2001).

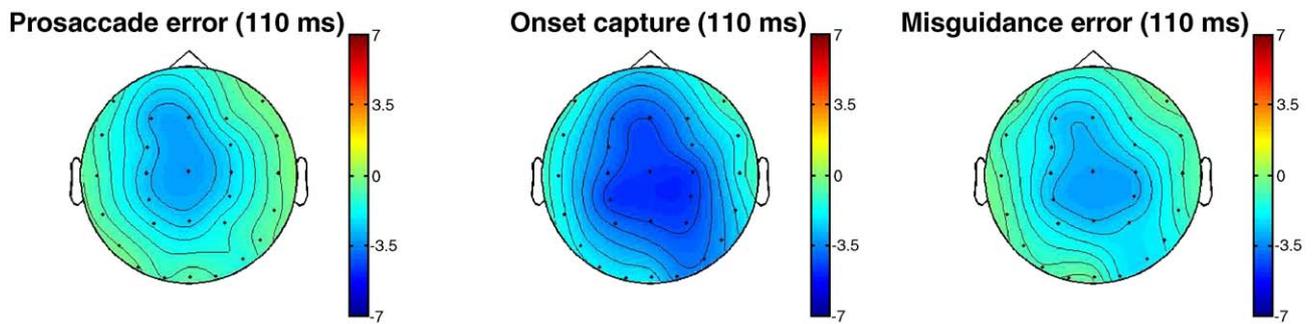


Fig. 3 – Topographical maps for difference waveforms (error minus correct) for prosaccade errors, onset capture errors and misguidance errors.

The ERN was detected on error trials (prosaccade, onset capture and misguidance errors) relative to correct trials ($F(1,8) = 24.05$, $P < 0.005$).¹ Although, there was a significant main effect of the electrode site ($F(2,16) = 9.15$, $P < 0.01$) the ERN amplitude was not different across the electrode sites ($F(2,16) = 0.12$, $P = 0.88$).

Although it appeared that ERN amplitude was greater for the onset capture errors than for the prosaccade and misguidance errors, this difference was not statistically significant ($F(2,16) = 1.10$, $P = 0.33$). This is also illustrated in the individual subject plots of the mean ERN amplitude for each eye movement type in Fig. 2B. A considerable overlap in the ERN amplitude for the erroneous saccades suggests that the lack of statistically significant difference is not a result of insufficient statistical power. In addition, a clear difference in the distribution between erroneous and correct saccades suggests that our design was not underpowered for these differences to be detected.

3. Discussion

In the present study, we examined whether deviations from optimal performance caused by the presence of a task-irrelevant event are detected by a performance-monitoring system reflected by the error-related negativity. Typically, erroneous responses are explicitly defined by the task instructions, for example, responding with a wrong key (“errors of choice”) or failure to withhold a certain predefined response (“errors of action”). Therefore, in these cases, action outcome can be compared with external standards and remedial processes can be activated to correct the performance when deviations from the standard are discovered. However, in the real world, there are many distractions and there often exist multiple ways of achieving the same goal. The question that remains is whether people adopt an internal performance standard, which is defined in terms of

¹ To control for potential differences in the signal-to-noise ratio due to a different number of trials in the conditions, we matched the number of trials and found no critical changes in the waveforms. The ERN was detected on error trials ($F(1,8) = 23.45$, $P < 0.005$) and there was no differences among different types of errors ($F(2,16) = 0.56$, $P = 0.58$). If anything, after the matching, the difference between the ERN amplitude for the onset capture and other types of errors appeared slightly decreased.

an optimal (i.e. faster, more accurate, etc.) goal achievement. Some evidence for that has been provided by the finding that slow, but correctly executed responses elicit an ERN even in the absence of an external response deadline (Coles et al., 2001). It has also been shown that patients with obsessive-compulsive disorder tend to generate a larger ERN, suggesting a possible disruption in their internal goal standard (Gehring et al., 2000).

Although it can be difficult to come up with a situation, in which a completely task-irrelevant event triggers a manual response and causes a deviation from the task goal, the visual system is constantly confronted with such disruptions, more often referred to as stimulus-driven capture of overt attention, or oculomotor capture. Such interruptions are usually very brief (less than 100 ms) and are quickly corrected (Theeuwes et al., 1998; 1999). Often, there is no subjective awareness of such disruptions taking place.

The combination of the antisaccade and oculomotor capture paradigms used in the present study provides an interesting framework in which to examine stimulus-driven errors, along with a baseline comparison to task-defined prosaccade errors. As in the typical oculomotor capture paradigm (Theeuwes et al., 1998, 1999), the onset had no stimulus–response mappings associated with it, since participants did not need to attend or process it in order to successfully complete the task. On the other hand, prosaccade errors were explicitly defined by the task instructions, since participants had to attend to the color singleton and to look away from it. Both oculomotor capture and prosaccade errors were observed in this task, along with misguidance errors, when the eyes first went in the direction of another distractor. These misguidance errors most likely represent a result of incorrect guessing: they seem to be less impulsive and more strategic than either prosaccade or oculomotor capture errors, since they had a slightly longer latency and were slightly larger in amplitude.

We found that all eye movement errors (prosaccade, onset capture and misguidance errors) observed in the hybrid task elicited a similar ERN. The fact that prosaccade errors elicited an ERN replicated previous findings (Nieuwenhuis et al., 2001), despite the fact that antisaccade had to be made away from the color singleton. The ERN elicited by the prosaccade (defined by the task) and misguidance errors (incorrect guessing) illustrate the detection of a deviation from an external standard. A clear ERN elicited for the onset

capture errors suggests that participants adopted an internal standard for a direct eye movement to the target and any eye movement that deviated from this standard was treated as incorrect. The ERN was elicited even when the error was not defined by the task and did not have to be maintained as a part of task-set on every trial (as prosaccade errors were in the antisaccade task).

It is worth noting that in our antisaccade-onset capture hybrid task participants had to make a saccade away from a color singleton, whereas in the typical antisaccade task (Hallet, 1978; Nieuwenhuis et al., 2001) participants had to make a saccade away from an onset cue. Nevertheless, participants made a number of erroneous eye movements in the direction of the color singleton, as well as erroneous eye movements in the direction of the onset. This is a first demonstration of prosaccade errors to a color singleton in the antisaccade paradigm. There is some evidence that onset transients, but not static singletons (i.e. color), directly generate activity in superior colliculus (SC), a midbrain structure, heavily involved in eye movement control (Trappenberg et al., 2001). Therefore, it could be the case that the prosaccade errors in our version of the antisaccade task are mediated by different brain structures than prosaccades that are traditionally observed with onset cues.

To summarize, the present study using a novel antisaccade-capture hybrid task demonstrated that in addition to an external standard provided by the task, an internal standard is defined by a participant. Any interruption or deviation of the ongoing goal-directed activity from an optimal and efficient goal achievement is detected by a performance-monitoring system indexed by the error-related negativity.

4. Experimental procedures

4.1. Participants

Nine right-handed individuals between 19 and 30 years old (average age 23, 4 males) were paid to participate in the experiment. All participants had normal or corrected to normal visual acuity and normal color vision, tested by the Ishihara Color Blindness Test (Ishihara, 1989). The data from two participants were replaced due to insufficient number of prosaccade errors (<2.7% in the onset present condition and <5% in the control condition).

4.2. Stimuli and procedure

Stimuli were presented in 16-bit color depth on 21-inch SVGA monitor controlled by a Dell 2.8 GHz computer. Participants' heads were stabilized by means of a chin rest located 70 cm from the monitor. Participants viewed displays containing four equidistant gray circles (3.5° in diameter, 1 pixel wide, luminance 21 cd/m²) each containing a small gray figure 8 (0.1° by 0.2°) presented on an imaginary circle with a radius of 9.7° (Fig. 1). The four circles appeared either at the clock positions 1, 5, 7 and 11 (arrangement 1) or at 2, 4, 8 and 10 (arrangement 2). Two different arrangements of stimuli were used in order to have the same locations for the onset capture trials and the

correct trials to control for differential contribution of eye movement artifact to the EEG recorded on these trials.

After 1000 ms, all the gray circles but one changed their color to equiluminant red. At the same time, the center fixation point changed from a "star" to a "plus" sign (0.3°). In the onset present condition, in addition to the four circles, an extra red circle with a gray figure '8' was added to the display simultaneously with the color change. 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 always be ± 90° away from the gray circle.

Participants performed a total of 160 trials in the control condition, in which no additional circle was present (i.e. pure antisaccade task), and 480 trials in the onset condition. Trials from the two conditions were randomly intermixed and the control condition occurred on 25% of the trials.

Participants were instructed to move their eyes away from the uniquely colored gray circle toward the red circle that was diagonally across from it as soon as they detected the color change in the periphery. They were asked to fixate the center of that red circle (the figure '8') until the display disappeared (1200 ms). Participants completed 10 practice trials prior to the experiment. Speed of eye movement initiation was stressed throughout the session in order to ensure an adequate number of errors to enable the examination of the questions described above. This was accomplished by giving the participants' feedback about their average saccadic latency every 2 blocks of trials (every 32 trials), and asking them to improve it.

4.3. Recording system

Eye position of the left eye was monitored online and recorded with an ASL 504 infra-red remote eye tracker, with a 60 Hz temporal resolution and better than 0.5° spatial resolution (Applied Science Laboratories, <http://www.a-s-l.com>).

Electrophysiological data were acquired using SynAmps amplifier and Neuroscan software (Compumedics Neuroscan). The EEG was recorded using a 32-channel QUIK-CAP with electrodes 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 mounted according to the extended 10–20 System. During the recording, the left mastoid (A1) served as a reference electrode. Prior to averaging, data were re-referenced offline to the algebraic average of two mastoids, $X_t - (1/2)(A2_t)$, where X is the electrode and t is the time point in ms. Vertical electrooculogram (EOG) was recorded using a pair of electrodes placed above and below the left eye in line with the pupil. Horizontal EOG was recorded from electrodes attached adjacent to the outer canthus of the left and right eyes. All impedance levels were kept below 10 kΩ. EEG and EOG signals were amplified with a bandpass of 0.1–50 Hz and digitized at 250 Hz. The gain was 5000 for the EEG channels and 500 for the EOG channels.

4.4. Data analysis

Eye movement data were analyzed using custom software, which allowed plotting the raw data for every trial for

verification purposes and performing offline drift correction. An eye movement was considered a saccade when the movement distance from the center fixation exceeded 1.5°. The saccadic latency was defined as the time between the color change and the onset of the first eye movement. 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 within a wedge $\pm 22.5^\circ$ of arc to the left or to the right of that object. Such a criterion was chosen to maximize the number of capture trials by including the so-called redirected saccades, when the eyes first went in the direction of the onset, but then without stopping, changed the direction to the target (Godijn and Theeuwes, 2002). Since the fixations on the onset can be quite brief (<100 ms), we used the following algorithm to calculate fixation durations: 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.

EEG data were analyzed using EEGLAB toolbox (Delorme and Makeig, 2004). All ERP waveforms were time-locked to the onset of the first saccade. EEG and EOG were epoched offline into periods of 600 ms, starting 100 ms prior to the onset of the initial saccade and ending 500 ms post-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 neurally generated EEG sources, based on assumptions of temporal independence of spatially overlapping sources (Jung et al., 2000; Makeig et al., 1999). It performed well in filtering out the artifacts due to diagonal eye movements in the present paradigm, as indexed by reduction of the EOG amplitude and by visual inspection of the corrected and uncorrected EEG on single epochs and in the averages.

EEG was averaged separately for correct trials (saccade went to the antisaccade target), the prosaccade errors (saccade was first directed to the color singleton), the onset capture errors (saccade was first directed to the irrelevant onset) and the misguidance errors (saccade was first directed to another distractor). To control for stimulus-related activity in the response-locked 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 (11% of trials, $M = 352$ ms, $SD = 47$ ms). Statistical analysis was focused on three midline electrode sites (Fz, Cz and Pz). The amplitude of ERN was quantified as the mean amplitude within the latency windows of 90–150 ms post-saccade relative to the mean voltage between 100 and 50 ms in the pre-saccade baseline. Eye movement and ERP difference between erroneous eye movements (averaged over the prosaccade, onset capture and misguidance errors) and correct saccades were analyzed with one-way repeated measures analyses of variance (ANOVA). Different types of eye movement errors (prosaccade, onset capture and misguidance) were then compared using a three-way ANOVA and if needed, followed up with post hoc analyses with the Bonferroni correction. Whenever necessary, probability values were adjusted using Geisser–Greenhouse correction for non-sphericity. Analyses were focused on the onset present condition since the results in the control condition were very

similar, but often had an insufficient number of trials for statistical testing (the no-onset control condition was presented only on 25% of all trials).

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