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Review

Performance monitoring in autism spectrum disorders: A systematic literature review of event-related potential studies

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ABSTRACT

Autism spectrum disorder (ASD) is marked by impairments in social–emotional situations, executive functioning, and behavioral regulation. These symptoms may be related to deficits in performance monitoring, i.e., the ability to observe and evaluate one's own behavior and performance which is necessary for the regulation of future behavior. The present literature review investigated electroencephalic correlates of performance monitoring in ASD. Event-related potentials (ERPs) considered in this review included internal performance monitoring components (error-related negativity, error positivity), external performance monitoring components (feedback-related negativity, feedback-P3), and observational performance monitoring components (observer error-related negativity, observer feedback-related negativity). The majority of studies point to reduced internal performance monitoring in ASD. External performance monitoring in reward-processing paradigms, where rewards are independent of performance, seems to be intact in ASD. So far, no studies have investigated the observer error-related negativity in ASD. Available data on the observer feedback-related negativity are inconclusive, since only two studies with differential study results investigated this construct in ASD. In general, results suggest that individuals with ASD have problems with internal performance monitoring and with learning from external, abstract feedback. In contrast, the processing of external, concrete feedback seems to be largely intact in ASD.

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1. Introduction

Autism spectrum disorder (ASD) is a pervasive neurodevelopmental disorder characterized by qualitative impairments in social communication and interaction, along with restrictive and repetitive behaviors, interests, and activities (American Psychiatric Association, 2013). To date, knowledge of the etiology of ASD is limited. ASD is a heterogeneous disorder, often accompanied by comorbid disorders and with no single cause or biological marker that can account for the variety of symptoms associated with it (Happé et al., 2006). The core symptoms of ASD lie within the domain of social interaction and communication. It has been shown that individuals with ASD have deficits in empathy-related processes, such as inferring other people's emotional and mental states as well as in adequately responding to these states (e.g. Baron-Cohen et al., 1985). In addition, executive functioning (EF) is often impaired in ASD and may contribute to difficulties in everyday function in affected individuals (Eigsti, 2011). For example, deficits in cognitive flexibility and planning, has been demonstrated in a multitude of studies (see Hill, 2004; Russo et al., 2007 for reviews). One important aspect of EF is *performance monitoring*; the ability to observe and evaluate one's own behavior and performance necessary for regulating future

behavior. Intact performance monitoring is integral to goal-directed and adaptive behavior. Previous studies suggest that performance monitoring may be altered in ASD, contributing to the social and cognitive deficits seen in individuals with ASD (Mundy, 2003). Therefore, the aim of the present literature review was to gain a better understanding of performance monitoring processes in ASD and their possible links to behavioral and cognitive symptoms associated with the disorder.

A better understanding of neurocognitive mechanisms associated with ASD may provide insight into inter-individual differences. Identifying where these differences exist is crucial for facilitating improved treatment options. It is therefore important to find ways for studying performance monitoring in ASD. Frequently utilized tools to study performance monitoring are electroencephalogram event-related potentials (ERPs; Falkenstein et al., 1990; Gehring et al., 1993; Miltner et al., 1997). As these neural indices appear to be particularly reliable in indexing performance monitoring processes (Olvet and Hajcak, 2009; Segalowitz et al., 2010), we reviewed studies utilizing electrophysiological means to study performance monitoring in ASD.

Performance monitoring involves the continuous tracking of ongoing actions and the detection of conflicting behavior or errors. Evaluating whether executed actions match intended outcomes is thus an essential part of performance monitoring; this function is referred to as *internal performance monitoring*. However, individuals may also monitor consequences of behavior, for example by considering feedback, in order to modify their behavior accordingly, which is called *external*

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performance monitoring. Another aspect of performance monitoring, the so-called *observational performance monitoring*, refers to the ability to use information gained from the observation of other individuals committing errors or receiving feedback on their actions in order to regulate one's own behavior.

An important neural source of performance monitoring is the anterior cingulate cortex (ACC) which appears to be implicated in all types of performance monitoring. For neurotypical (NT) adults, there is converging evidence that the same region of the ACC is implicated in internal- and external performance monitoring (Holroyd et al., 2004b) as well as in observational performance monitoring (Shane et al., 2008). Individuals with ASD often show abnormalities in the ACC (Haznedar et al., 2000; Mundy, 2003) and have difficulties in altering their behavior in response to environmental demands. For example, it has been shown that children with ASD have difficulties self-correcting their errors (Russell and Jarrold, 1998) and do not show post-error slowing in reaction time tasks as opposed to NTs (Bogte et al., 2007). Hence, these behavioral studies on performance monitoring and abnormalities in the ACC are indicative of potentially deficient performance monitoring in ASD.

It has been suggested that deficits in EF may contribute to the empathy related difficulties in ASD (Hughes and Russell, 1993; Ozonoff et al., 1991). Individuals with ASD have a reduced ability to act appropriately to socio-emotional stimuli and to use information about the mental states of others for guiding their own behavior, which may be explained by impairments in primarily cognitive empathy (Dziobek et al., 2008; Rogers et al., 2007; Schwenck et al., 2012). EFs are thought to facilitate these empathic processes (Decety and Meyer, 2008; Mahy et al., 2014). Indeed, higher levels of self-reported empathy have been found to be related to better internal performance monitoring in the general population (Larson et al., 2010). Cognitive aspects of empathy in particular seem to be related to performance monitoring (Larson et al., 2010), and deficits in cognitive empathy specifically are associated with ASD (Dziobek et al., 2008; Rogers et al., 2007; Rueda et al., 2015; Schwenck et al., 2012). Furthermore, the ACC is also central to empathy (Bernhardt and Singer, 2012). Thus, brain regions responsible for empathy and performance monitoring share a common neural structure, further suggesting a relationship between performance monitoring and empathy.

1.1. Performance monitoring components

ERP components are often used as indices of performance monitoring. One ERP component which has been linked to internal performance monitoring is the error-related negativity (ERN; also referred to as Ne), occurring 50–100 ms after error commission in cognitive performance paradigms (Falkenstein et al., 1990; Gehring et al., 1993). The ERN is often followed by a slow-going positive deflection, the error positivity (Pe), peaking at around 200–500 ms following an erroneous response (Falkenstein et al., 2000). Whereas the Pe seems to reflect the conscious recognition of an error, being only present when participants are aware of their errors, the ERN can also be observed when participants are unaware of their errors (Overbeek et al., 2005). In their review, Overbeek et al. (2005) identified further differences between the ERN and the Pe: while the Pe seems to be similar across different age groups, the ERN has been found to be smaller in children than in adults. Moreover, ERN, but not Pe, amplitude appears to be affected by medication use, while the Pe, but not the ERN, appears to differ across different cognitive paradigms. However, a recent study pointed out that different paradigms do demonstrate differences in ERN (and Pe) amplitudes, possibly related to task difficulty (Riesel et al., 2013).

In the context of external performance monitoring, the feedback-related negativity (FRN) has been mentioned. It is elicited by negative feedback and loss delivery in reward-processing paradigms and peaks at around 250 ms to 300 ms post-stimulus (Miltner et al., 1997; Gehring and Willoughby, 2002). The magnitude of gains and losses

does not seem to influence FRN amplitude (Hajcak et al., 2006), reflecting a binary “good versus bad” evaluation of outcomes. The evaluation of “good versus bad” is however not based on the objective value of the outcome, but on its value relative to the value of remaining outcomes (Holroyd et al., 2004a). In relation to external performance monitoring, the feedback-P3 has also been mentioned, which peaks at around 300–600 ms post-stimulus (Goldstein et al., 2006). In contrast to the FRN, the feedback-P3 does seem to reflect objective magnitude of outcome, such that an increase in reward outcome is accompanied by an increase in P3 amplitude (Yeung and Sanfey, 2004).

Observing another person committing an error also elicits a negative-going ERP, the observer ERN (oERN), largest at around 230–250 ms post-stimulus with a pattern similar to the classic ERN (Carp et al., 2009; Miltner et al., 2003; van Schie et al., 2004). Likewise, an observer FRN (oFRN), with a pattern similar to the FRN is elicited when observing another person receiving negative feedback (Kang et al., 2010; Yu and Zhou, 2006).

Neural sources of the performance monitoring ERPs have been studied as well. The ERN, FRN, oERN and oFRN all seem to be generated by the ACC (Dehaene et al., 1994; Kang et al., 2010; van Schie et al., 2004). For the ERN and FRN, it has been proposed that the ERN and FRN are generated by phasic suppression of dopaminergic activity, conveying a reinforcement learning signal to the ACC, representing worse than expected outcomes (Holroyd and Coles, 2002). This may also hold for the oERN and the oFRN, given their common neural generator – the ACC – with the ERN and FRN. The ACC has also been mentioned to be the neural generator of the Pe. However, the exact neural source of the Pe is more difficult to determine and less well studied with inconsistent findings (Vocat et al., 2008; Herrmann et al., 2004; van Veen and Carter, 2002). To our knowledge, potential neural sources of the feedback-P3 have not been investigated yet. An overview of the described ERPs may be found in Table 1.

1.2. Aims and outline of the present literature review

The aim of the present review was to investigate electrophysiological correlates of performance monitoring in individuals with ASD. Additionally, we investigated whether particular characteristics of ASD are related to performance monitoring and whether aspects of empathy are related to ERP components indexing performance monitoring in ASD. Also, relationships were sought between performance monitoring and both ASD symptoms in specific and comorbid symptoms (e.g. internalizing problems) in general. In the Results section, findings regarding internal, external and observational performance monitoring components in ASD are presented. These findings are discussed in light of methodological and sampling differences between studies, such as the task paradigm used, quantification of ERP components or medication use. Furthermore, we examined the relationship between the presence of rewards and performance monitoring in ASD, as brain-imaging studies point to altered reward-processing in ASD (Delmonte et al., 2012; Dichter et al., 2012; Richey et al., 2014). It has been demonstrated that motivation affects performance monitoring in NT adults (e.g. Hajcak et al., 2005), and that the presence or absence of rewards may be an additional factor influencing performance monitoring (Ridderinkhof et al., 2004). In the context of external performance monitoring studies in particular, rewards appear to play an important role as performance feedback often indicates the gain or loss of reward in such studies (Hajcak et al., 2006). Based on the findings of the present review, hypotheses for future research are formulated.

2. Methods

Studies were searched from the databases PubMed and PsycInfo (last search was carried out on August, 23rd, 2015) using the search terms “autism” in combination with “ERN”, “error negativity”, “error positivity”, “FRN”, “feedback negativity”, or “feedback positivity”. Additional

Table 1
Overview of reviewed performance monitoring event-related potentials (ERPs).

ERP component	Type of performance monitoring	Polarity	Scalp distribution	Peak latency and event
ERN	Internal	Negative	Fronto-central electrode sites	50–100 ms after error commission
Pe	Internal	Positive	Diffuse parieto-occipital distribution	200–500 ms after error commission
FRN	External	Negative	Fronto-central electrode sites	250–300 ms after receiving negative feedback/loss delivery
Feedback-P3	External	Positive	Centro-parietal electrode sites	300–600 ms after receiving negative feedback/loss delivery
oERN	Observational	Negative	Fronto-central electrode sites	Elicited by observing another person committing an error; 230–250 ms after error commission
oFRN	Observational	Negative	Fronto-central electrode sites	Elicited by observing another person receiving negative feedback; 250–300 ms after presentation of negative feedback

Note. Internal performance monitoring ERPs can be observed following errors in cognitive performance paradigms, whereas external performance monitoring ERPs can be observed following error feedback or delivery of losses, and observational performance monitoring ERPs can be elicited by observing someone else making an erroneous response or receiving negative feedback.

ERN = error-related negativity; Pe = error positivity; FRN = feedback-related negativity; oERN = observational error-related negativity; oFRN = observational feedback-related negativity.

studies were identified from the reference lists of articles obtained from the online searches. Duplicates of records were removed and titles and abstracts of remaining records were screened. Finally, full-text articles were assessed for eligibility. For inclusion, studies were required to be written in English, to have investigated a group of patients with ASD and a NT group, and to have assessed at least one of the ERP components of interest (ERN, Pe, FRN, feedback-P3, oERN, and oFRN) in both groups while participants performed a computerized cognitive task. Studies were only included in the review when the ASD diagnoses of participants were confirmed by diagnostic instruments specific for ASD, such as the Autism Diagnostic Observation Schedule ADOS (ADOS; Lord

et al., 2002), or the Social Communication Questionnaire (SCQ; Rutter et al., 2003).

Identified studies were categorized into the following subgroups: *internal performance monitoring*, including ERN and Pe studies, *external performance monitoring*, including FRN and feedback-P3 studies, and *observational performance monitoring*, including oFRN and oERN studies. For each component, the following confounding factors were inspected: ASD symptoms, IQ, medication use, and age. Furthermore, in order to facilitate comparison, effect sizes (Cohen's *d*) were calculated when sufficient data was presented. According to Cohen's conventional guidelines effect sizes of $d \geq 0.20$ are considered to be small, whereas effect sizes of

Fig. 1. PRISMA flow diagram. The diagram depicts the selection of studies according to the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

Table 2
Study characteristics and results.

Authors	Subjects: n group	Sex (male/female)	Age (M ± SD in years)	Controlled variables	Task/paradigm	ERP measures			Results
						ERP component	Amplitude measure	Window (in ms post-event)	
Internal performance monitoring									
Groen et al. (2008)	19 ASD	15/4	11.4	Age, gender, IQ, sex, handedness	Probabilistic learning paradigm: Random presentation of four stimuli types (pictures A, B, C, D) Participants had to learn correct responses by attending to performance feedback.	ERN (Fz)	Mean	− 40 to 80	ASD = NTs (Cohen's <i>d</i> = 0.12 for the whole task; <i>d</i> = 0.33 for the second part of the study) ASD = NTs (Cohen's <i>d</i> = 0.23) ASD = NTs (Cohen's <i>d</i> = 0.33)
	18 NT (+ 35 ADHD)	12/6	± 0.9 11.4 ± 0.9			Pe (Pz)	Mean	100–800	
Henderson et al. (2006)	24 ASD 17 NT	22/2 14/3	11.38 ± 2.06 11.4 ± 1.86	Age, gender, IQ	Flanker task: 5-arrow-arrays, e.g. <<>><<	ERN (FCz)	Baseline-to-peak	0–150	ASD = NTs (Cohen's <i>d</i> = 0.33)
Henderson et al. (2015)	38ASD 36 NT	34/4 27/9	13.16 ± 2.49 12.61 ± 2.39	Verbal IQ, age, ethnicity, (gender was comparable)	Flanker task: 5-arrow-arrays, e.g. <<>><<	ERN (average of Fz and FCz)	Mean	− 20 to 100	ASD = NTs (Cohen's <i>d</i> = 0.39)
McMahon and Henderson (2014)	42 ASD 42 NT	38/4 36/6	15.17 ± 2.68 15.16 ± 2.90	Performance IQ, age, gender note: verbal IQ approached significance, which was considered in analyses	Face-processing task: 2 conditions (all participants completed both conditions) • Gender task: identification of whether face was male or female • Affect task: identification of whether face was angry or sad	ERNdiff (average of FCz and Cz)	Mean	25–75	- Gender condition: ASD < NTs (Cohen's <i>d</i> = 2.81) - Affect condition: ASD = NTs (Cohen's <i>d</i> = 0.07)
Santesso et al. (2011)	13 ASD	9/4	36.0	Sex, age, IQ	Flanker task: 3-digit-arrays, e.g. “333” or “434”	ERN (FCz)	Baseline-to-peak	50–100	ASD < NTs (Cohen's <i>d</i> = 0.85) ASD < NTs (Cohens's <i>d</i> = 0.82) ASD = NTs (Cohen's <i>d</i> = 0.32) ASD < NTs (Cohen's <i>d</i> = 0.89) ASD < NTs (Cohen's <i>d</i> = 0.84)
	16 NT	12/4	± 11.1 35.7 ± 10.6			ERNdiff	Baseline-to-peak	50–100	
						CRN (FCz)	Baseline-to-peak	50–100	
						Pe (FCz)	Baseline-to-peak	200–400	
Sokhadze et al. (2010)	14 ASD	11/3	13.0	Age, IQ, SES, handedness	Visual oddball task: • 2 target letters (“X”, “O”); 4 distractors (“v”, “<”, “^”, “>”) • Participants were instructed to press a key when the target letter appears • Probability of stimuli presentation: “O”: 50%; “X”: 25%; distractors: 25%	ERN (several averaged channels at fronto-central sites)	Mean	40–150	ASD = NTs (Cohen's <i>d</i> = 0.56)
	14 NT	9/5	± 2.5 14.1 ± 3.9			Pe (several averaged channels at fronto-central sites)	Mean	100–200	
Sokhadze et al. (2012)	16 ASD	14/2	12.6	Age, IQ, SES	Visual oddball task: Kanizsa figures • 4 stimulus types: Kanizsa square (target), Kanizsa triangle, non-Kanizsa square, and non-Kanizsa triangle	ERN (several averaged channels at fronto-central sites)	Mean	40–150	ASD < NTs (Cohen's <i>d</i> = 0.99)
	16 NT (+ 16 ADHD)	13/3	± 2.3 14.6 ± 3.9			Pe (several averaged channels at fronto-central sites)	Mean	100–200	

South et al. (2010)	24 ASD 21 NT	22/2 20/1	14.03 ± 2.40 14.23 ± 2.83	Age, IQ	<ul style="list-style-type: none"> Participates were instructed to press a key when the target appears Probability of stimuli presentation: 25% for every stimuli Flanker task: 3-arrow-arrays, e.g. « > »	averaged channels at fronto-central sites)	Mean	0–100	d = 0.43)
						ERN (average of 4 fronto-central sites)	Mean	0–100	ASD < NTs (Cohen's d = 0.76)
						CRN (average of 4 fronto-central sites)	Mean	200–400	ASD = NTs (Cohen's d = 0.21)
Vlamings et al. (2008)	17 ASD 10 NT	16/1 10/0	10.42 ± 2.04 9.23 ± 1.20	Age, IQ, initial positivity at electrodes (Fz and FCz)	Auditory decision task: 4 different animal sounds (cat, dog, sheep, pig) <ul style="list-style-type: none"> Easy condition: right-hand button-press for cat sound; left-hand button-press for other sound Hard condition: right-hand button-press when sound was the same as the preceding sound; left-hand button-press when the sound was dissimilar 	Pe (average of 7 centro-parietal electrode sites)	Mean	200–400	ASD = NTs (Cohen's d = 0.01)
						ERN (FCz)	Peak-to-peak	Difference between the mean area amplitude in a window (110–50 ms) surrounding the first positive peak before response and the mean area amplitude in a window (30–70 ms) surrounding the first negativity post-response	ASD < NTs (Cohen's d = 1.17)
						CRN (FCz)	Mean	Difference between the mean area amplitude in a window (110–50 ms) surrounding the first positive peak before response and the mean area amplitude in a window (30–70 ms) surrounding the first negativity post-response	ASD = NTs (Cohen's d = 0.48)
External performance monitoring Bellebaum et al. (2014)	10 ASD 12 NT	1/9 3/9	30.0 ± 5.0 27.0 ± 5.7	Age, IQ	Probabilistic reward-learning task: (presentation of pairs of Asian symbols: AB, CD, EF; participants were required to choose one of the stimuli)	Pe (Pz)	Mean	250–500	ASD < NTs (Cohen's d = 0.70)
						FRN (Cz)	Peak-to-peak	Difference between the most negative peak 200–350 ms after feedback presentation and the preceding most positive peak	ASD < NTs (d = 0.95 irrespective of learning type and feedback valence)
						Feedback-P3 (Pz)	Mean	300–500	ASD = NTs
Groen et al. (2008) ^a	19 ASD 18 NT (+ 35 ADHD)	19 ASD 18 NC (+ 35 ADHD)	11.4 ± 0.9 11.4 ± 0.9	Age, gender, IQ, sex, handedness	<ul style="list-style-type: none"> Active learning Observational learning Feedback: non-social; on computer screen Reward: monetary, tied to stimuli				
Groen et al. (2008) ^a	19 ASD 18 NT (+ 35 ADHD)	19 ASD 18 NC (+ 35 ADHD)	11.4 ± 0.9 11.4 ± 0.9	Age, gender, IQ, sex, handedness	Probabilistic learning paradigm Random presentation of four stimulus types (pictures A, B, C, D) Participants had to learn correct responses by attending to performance feedback. Feedback: non-social, on computer screen (green square: positive feedback; red square: negative	Early interval (before 450 ms after feedback) of feedback-P3 (Pz)	Mean	200–1000	ASD = NTs
						Later interval	Mean	200–1000	ASD < NTs (Cohen's

(continued on next page)

Table 2 (continued)

Authors	Subjects: n group	Sex (male/female)	Age (M ± SD in years)	Controlled variables	Task/paradigm	ERP measures			
						ERP component	Amplitude measure	Window (in ms post-event)	Results
Larson et al. (2011)	25 ASD 25 NT	23/2 24/1	13.89 ± 2.46 14.07 ± 2.69	Age, IQ	feedback; black square: late responses)		(450–1000 ms after feedback) of feedback-P3 (Pz)		<i>d</i> = 0.42 for the second part of the study)
					<ul style="list-style-type: none">Stimuli A and B were followed by informative feedbackStimuli C and D were followed by uninforma- tive feedback (feedback valence for stimulus C was always positive; feedback valence for pic- ture D was always negative) Reward: points (children started with 52 points and could maximally achieve 100 points)				
					<ul style="list-style-type: none">1 point win1 point lossLate responses: loss of 2 points Note: all children received a toy at the end of the experiment, irrespective of performance Reward probability: tied to stimuli type (see feedback)				
McPartland et al. (2012)	26 ASD 28 NT	17/9 22/6	11.22 ± 2.52 12.08 ± 0.95	Age, gender, ethnicity, handedness, IQ	Guessing game Participants were required to choose one of 4 different-colored balloons	FRN (Fz)	Peak-to-peak	125–350	ASD = NTs (Cohen's <i>d</i> = 0.35) ASD = NTs (Cohen's <i>d</i> = 0.13) ASD = NTs (Cohen's <i>d</i> = 0.13)
					Feedback: non-social, on computer screen	FRNdifff (Fz)	Peak	Most negative amplitude of the difference wave 125–350 ms post-feedback	
					Reward: monetary	Feedback-P3 (Pz)	Baseline-to-peak	300–600	
Stavropoulos and Carver (2014)	20 ASD 23 NT	19/1 22/1	8.28 ± 0.23 7.47 ± 0.21	Gender, IQ	<ul style="list-style-type: none">25 cent win25 cent loss Reward probability: 50%	FRNdifff (average across four frontal electrodes)	Peak	Most negative amplitude of the difference wave 250–300 ms post-feedback	ASD = NTs (Cohen's <i>d</i> = 0.15)
					Guessing game Participants were required to choose one of 4 different-colored balloons				
					Feedback: non-social; on computer screen for 1000 ms (green dollar sign indicating a win; empty white box indicating a draw) Reward: monetary				
Stavropoulos and Carver (2014)	20 ASD 23 NT	19/1 22/1	8.28 ± 0.23 7.47 ± 0.21	Gender, IQ	<ul style="list-style-type: none">10 cent winNo losses Reward probability: exceeded 50% (“win and “draw” outcomes were equal probable with 3 additional winning trials)	FRN (Fz, FCz, Cz)	Mean	300–450	- Social feedback condition: ASD = NTs (Cohen's <i>d</i> = 0.29) - Non-social feedback condition: ASD = NTs (Cohen's <i>d</i> = 0.23)
					Guessing game Participants were required to choose one out of two stimuli				
					Feedback: two conditions				
Stavropoulos and Carver (2014)	20 ASD 23 NT	19/1 22/1	8.28 ± 0.23 7.47 ± 0.21	Gender, IQ	<ul style="list-style-type: none">social (picture of smiling of frowning human face)non-social (arrow pointing upwards or downwards) Reward: cracker of fruit snack (depending on participant's preferences)				

Observational monitoring					Reward probability: 50%					
Bellebaum et al. (2014) ^b	10 ASD 12 NT	1/9 3/9	30.0 ± 5.0 27.0 ± 5.7	Age, IQ	Paradigm	Probabilistic reward-learning task (presentation of pairs of Asian symbols: AB, CD, EF; participants were required to choose one of the stimuli) • Active learning • Observational learning Feedback: non-social; on computer screen Reward: monetary (tied to stimuli); • 20 cent win • 10 cent loss Reward probability: Dependent on stimuli pairs • AB pair: A 80% chance of winning; B 20% chance of winning • CD pair: C 70% chance of winning; D 30% chance of winning • EF pair: E 60% chance of winning; F 40% chance of winning	oFRN (Cz)	Peak-to-peak	Difference between most negative peak 200–350 ms after feedback presentation and the preceding most positive peak	ASD < NTs (<i>d</i> = 0.95 irrespective of learning type and feedback valence)
Clawson et al. (2014)	38 ASD 32 NT	34/4 26/5	13.1 ± 2.5 12.4 ± 2.9	Age, IQ	Paradigm	Flanker task, 5-arrow-arrays, e.g. <<>><< • Participants observed an confederate performing the task • Participants were instructed to count the number of errors committed by the confederate Feedback: non-social; on computer screen, immediately following response of confederate (for 100 ms) Reward: • + 5 “points” for correct responses of confederate • – 5 “points” error responses of confederate Reward probability: dependent on performance of confederate	oFRN (FCz) oFRNdifff (FCz)	Mean Mean	320–350 320–350	ASD = NTs (Cohen's <i>d</i> = 0.26) ASD = NTs (Cohen's <i>d</i> = 0.17)

Note. ASD = autism spectrum disorder; NT = neurotypicals; ERP = event-related potentials; ADHD = attention-deficit/hyperactivity disorder; ERN = error-related negativity; Pe = error positivity; ERNdifff = difference wave between correct and incorrect trials; CRN = correct-related negativity; SES = socioeconomic status; FRN = feedback-related negativity; FRNdifff = difference wave between positive and negative feedback trials; oFRN = observer feedback-related negativity; oFRNdifff = difference wave between positive and negative feedback trials.

^a Study also mentioned in “Internal performance monitoring” section.

^b Study also mentioned in “External performance monitoring” section.

$d \geq 0.50$ and $d \geq 0.80$ are considered to be of moderate and large size, respectively (Cohen, 1977).

3. Results

The systematic literature search revealed 14 articles which examined performance monitoring in ASD fulfilling the inclusion criteria. Fig. 1 presents an overview of the systematic search. Characteristics of studies and calculated effect sizes can be found in Table 2. In addition, study results are presented graphically in Fig. 2 with studies showing significant differences between groups, studies that failed revealing significant differences and studies that found inconsistent results for different conditions (i.e. studies with several conditions which differed in reaching significant group differences).

3.1. Internal performance monitoring

3.1.1. ERN

In total, nine studies examining the ERN in ASD were identified. Of these, four studies utilized a variant of the Flanker task (Henderson et al., 2006, 2015; South et al., 2010; Santesso et al., 2011). Two studies used a visual oddball paradigm (equivalent to a continuous performance task), which required participants to only respond to an infrequently occurring target stimulus (Sokhadze et al., 2010, 2012). Vlamings et al. (2008) employed an auditory decision task in which participants were presented with one of four auditory stimuli and had to perform either a right-hand button press or a left-hand button press, depending on task instructions. The study consisted of two task conditions, differing in difficulty. A further study used a probabilistic learning paradigm in which four stimuli were randomly presented to participants (Groen et al., 2008). Participants had to learn correct responses by attending to performance feedback. Two stimuli were followed by informative feedback, whereas the remaining two stimuli were followed by uninformative feedback. Lastly, McMahon and Henderson (2014) employed a face-processing task with two conditions. One condition required participants to identify whether the presented face was male or female (gender-condition). The second condition required participants to identify whether the presented face was angry or happy (affect condition). Furthermore, this study defined the ERN as the difference in amplitude between correct and incorrect trials, creating a new variable (ERNdiff), whereas the remaining studies either investigated error trials only or used response type (correct versus incorrect) as a within-subject factor in repeated measures analyses of variance.

Five out of the nine ERN studies demonstrated reduced ERN amplitudes in patients with ASD as compared to NTs (Santesso et al., 2011; Sokhadze et al., 2010, 2012; South et al., 2010; Vlamings et al., 2008), with Cohen's d ranging from 0.76 to 1.17. In contrast, three studies could not reveal any statistically significant differences in ERN amplitude between ASD patients and NTs, with Cohen's d ranging from 0.12 to 0.39 (Groen et al., 2008; Henderson et al., 2006, 2015). The study examining face-processing found inconsistent results for the two conditions (McMahon and Henderson, 2014). The gender-condition, requiring participants to identify whether the face was male or female, revealed smaller ERN amplitudes in ASD patients as compared to NTs, with a large effect size ($d = 2.81$). In contrast, the affect-condition, requiring participants to identify whether the presented face was angry or happy, did not reveal a statistically significant difference ($d = 0.07$). McMahon and Henderson (2014) explained their findings in two ways. First, it may be the case that individuals with ASD are aware of the fact that, for them, consequences of errors are greater in social situations, causing ERN amplitudes to be increased and therefore being comparable to ERN amplitudes of NTs. Second, error-processing in more social situations might be more effortful, leading to reduced processing efficiency and enhanced ERNs, similar to the ERNs of NTs. Authors of all remaining studies with null results reported increased error rates in the clinical group relative to NTs (Groen et al., 2008;

Henderson et al., 2006, 2015), suggesting enhanced processing effort for individuals with ASD. Greater processing effort might have caused the ERN to be enhanced in individuals with ASD, being similar in amplitude to the ERN of NTs. Conversely, two out of five studies with significant differences in ERN amplitude between groups found equivalent error rates (Santesso et al., 2011; Vlamings et al., 2008). However, two studies with significant findings found higher error rates in the ASD groups (Sokhadze et al., 2010, 2012), and one study found a trend towards higher error rates in ASD as compared to NTs (South et al., 2010). Thus, a potential correlation between error rates and ERN amplitude remains to be further investigated.

Several studies examined factors related to ERN amplitude in ASD. For example, Henderson et al. (2015) found that ERN amplitude seems to be sensitive to ToM abilities, as measured by a composite score of "The Children's Eyes Test" (Baron-Cohen et al., 2001a) and "The Strange Stories Task" (Happé, 1994), such that larger ERN amplitudes were related to higher ToM scores. McMahon and Henderson (2014) conducted a hierarchical regression analysis predicting ToM abilities using the same composite scores. Results indicate that the ERNdiff did not significantly predict ToM abilities when the variables "diagnostic group", "age", and "verbal IQ" were already included in the model. However, this is not very surprising, since ERNdiff amplitude may be highly correlated with variables which were already included in the model and will therefore not add significant information if included into the model.

ASD symptomatology per se does not seem to be directly related to ERN amplitude and findings with regard to a potential relation between autistic symptoms and the ERN are inconsistent. In general, the majority of studies could not reveal any significant association between ERN amplitude and ASD symptomatology (Groen et al., 2008; McMahon and Henderson, 2014; Vlamings et al., 2008). Two studies found larger ERN amplitudes to be associated with fewer overall autistic symptoms (Henderson et al., 2006; Santesso et al., 2011). In contrast, Henderson et al. (2015) found that more autistic symptoms were associated with larger ERN amplitudes and South et al. (2010) could not reveal a significant relationship between autism severity and ERN amplitudes. Results of this review indicate that better social skills seem to be related to larger ERNs (Henderson et al., 2006; Santesso et al., 2011; South et al., 2010). However, Groen et al. (2008) could not find such an association. None of the reviewed studies reported associations between restrictive and repetitive patterns of behavior and ERN amplitude (Groen et al., 2008; Henderson et al., 2006; South et al., 2010; Vlamings et al., 2008).

Henderson et al. (2006) investigated the relationship between internalizing problems and ERN amplitude, and found that larger ERN amplitudes were related to less internalizing problems. This relation was however reduced to non-significance when controlling for verbal IQ and medication use. A subsequent study carried out by the same research group found that larger ERN amplitudes were related to more internalizing problems (Henderson et al., 2015). This relationship between increased ERN amplitudes in relation to more internalizing problems is in line with another study conducted by Groen et al. (2008) who found the same trend.

Several studies investigated a potential relation between intelligence and ERN amplitude. While one study found that larger ERN amplitudes were related to higher verbal IQ, the majority of studies could not find any relationship between (verbal) IQ and ERN amplitude (Henderson et al., 2015; McMahon and Henderson, 2014; Santesso et al., 2011; South et al., 2010; Vlamings et al., 2008). It should be noted that constructs, such as IQ and ASD symptomatology are broad constructs, comprising a range of abilities. Moreover, inter-individual differences are large and symptoms among patients with ASD are heterogeneous and may have differential effects on the ERN. Most studies did not control for differences in symptom presentation, which may have caused inconsistent findings. Therefore, it may be more efficient to investigate specific aspects of cognition or social functioning with

Fig. 2. Overview of performance monitoring ERPs in ASD. oFRN = observer feedback-related negativity; FRN = feedback-related negativity; CRN = correct-related negativity; Pe = error positivity; error-related negativity; ASD = autism spectrum disorder; NT = neurotypicals.

respect to the ERN, while controlling for other aspects known to influence ERN amplitude.

The effect of medication use is a further factor that may have caused inconsistencies across studies. The ERN is likely to be influenced by medication affecting the dopaminergic system (Overbeek et al., 2005). Henderson et al. (2006) reported that participants taking (stimulant and/or antidepressant) medication had larger ERN amplitudes. However, three further studies could not find any effects of atypical antipsychotic and antidepressant (Santesso et al., 2011), “psychotropic” (Henderson et al., 2015), or “psychoactive” medication (South et al., 2010) on ERN amplitude. Two further studies included participants taking medication (stimulants, mood stabilizers and antidepressants), but did not investigate or control for potential effects (Sokhadze et al., 2010, 2012). It should be noted that the studies investigating the effects of medication use all had small sample sizes, which may have impacted on the results of statistical analysis. For example, finding statistically significant differences in ERN amplitude between participants who used medication and those who did not is less likely when sample sizes are small. Moreover, different types of medication may have differential effects on ERN amplitude and it is therefore not advisable to include participants using different types of medication in one group.

Increasing age seems to be related to a larger ERNdiff (McMahon and Henderson, 2014). In contrast, Henderson et al. (2015) reported that ERNs were unrelated to age. Santesso et al. (2011) investigated the ERN in adults and found reduced amplitudes in ASD, compared to NTs. These group differences were unchanged when age was included as a covariate.

Importantly, none of the reviewed studies found differences in negativity after correct responses between groups (Henderson et al., 2015; Santesso et al., 2011; South et al., 2010; Vlamings et al., 2008), indicating that internal monitoring of correct responses in ASD is similar to that of NTs.

3.1.2. Pe

In total, six studies investigated the Pe. All these studies also examined the ERN (see Section 3.1.1). Two studies found significantly smaller Pe amplitudes in ASD patients relative to NTs, with medium ($d = 0.70$) to large ($d = 0.89$) effect sizes (Santesso et al., 2011; Vlamings et al., 2008), while four studies could not reveal any group differences in Pe amplitude, with Cohen's d ranging from 0.01 to 0.56 (see Table 2; Groen et al., 2008; Sokhadze et al., 2010, 2012; South et al., 2010). Santesso et al. (2011) investigated the effect of age on Pe amplitude and reported that group differences in Pe amplitude were slightly reduced when including age as a covariate. None of the remaining studies investigated a potential relationship between age and Pe amplitude.

Also, none of the studies explored a possible relationship between IQ and Pe amplitude.

Examination of a possible relationship between Pe amplitude and symptom presentation did not reveal any significant associations (Groen et al., 2008; Vlamings et al., 2008). Neither did antipsychotic, antidepressant (Santesso et al., 2011) or “psychoactive” medication (South et al., 2010) seem to influence Pe amplitude (Santesso et al., 2011; South et al., 2010). However, two studies included patients using medication (stimulants, mood stabilizers and antidepressants), but did not control or investigate potential medication effects (Sokhadze et al., 2010, 2012). Interestingly, there seems to be a relation between error rates and Pe amplitude. Specifically, all studies which found more errors in individuals with ASD as compared to NTs, which is indicative of more processing effort, reported equal Pe amplitudes across groups (Groen et al., 2008; Sokhadze et al., 2010, 2012; South et al., 2010), whereas all studies reporting equal error rates found decreased Pe amplitudes in ASD (Santesso et al., 2011; Vlamings et al., 2008). Increased processing effort may therefore increase Pe amplitudes in ASD, similar to what was observed on the ERN.

3.2. External performance monitoring

3.2.1. FRN

Our systematic search identified four studies investigating the FRN. Of those, most studies ($k = 3$) utilized a guessing game in which participants had to choose one out of several stimuli and where rewards were independent of performance (Larson et al., 2011; McPartland et al., 2012; Stavropoulos and Carver, 2014). None of the studies using a guessing game revealed statistically significant differences in FRN amplitude between ASD patients and NTs, with Cohen's d ranging from 0.13 to 0.35. A further study used a probabilistic learning paradigm, where the relative frequencies for a win were tied to different stimuli (Bellebaum et al., 2014), and where participants had to learn correct responses by attending to performance feedback. The authors of this study found a general reduction in FRN amplitudes in patients with ASD relative to NTs, which was irrespective of learning type (i.e. whether participants performed the task themselves, or observed a confederate performing the task) and irrespective of feedback valence (positive versus negative). Cohen's d for the difference in FRN amplitude, irrespective of learning type and feedback valence was found to be large ($d = 0.95$). Inconsistent findings between studies may thus have been caused by task differences. However, age and gender may also have been confounding factors. Participants in the Bellebaum et al. (2014) study were adults and mostly female, whereas participants of the remaining studies were children and adolescents and mostly male

(Larson et al., 2011; McPartland et al., 2012; Stavropoulos and Carver, 2014). Moreover, Larson et al. (2011) reported a significant positive correlation between age and FRN amplitude, indicating that increased age is related to more positive (i.e. reduced) FRN amplitudes in ASD (but not in NTs), which is in line with the findings of Bellebaum et al. (2014) pointing to reduced FRN amplitudes in adult ASD patients. Stavropoulos and Carver (2014), however, did not find a significant correlation between age and FRN amplitude.

Notably, Stavropoulos and Carver (2014) could not reveal the traditional main effect of feedback type (i.e. larger FRN amplitudes for negative as compared to positive feedback), making an interpretation of their results difficult. It might have been the case that feedback (arrows) and rewards (crackers or fruit snacks) were not salient and also not sufficiently appealing, leading to low motivation for participants to perform the task.

Two studies (Larson et al., 2011; McPartland et al., 2012) investigated IQ, ASD symptomology, or internalizing problems in relation to FRN amplitude, but did not reveal any significant correlations. Medication effects were not investigated. However, Bellebaum et al. (2014) included five ASD patients taking antidepressant medication and Stavropoulos and Carver (2014) included three ASD patients “taking medication in order to improve concentration”, while McPartland et al. (2012) explicitly reported having excluded participants taking any anticonvulsant medication.

In conclusion, the samples of studies included in this review were quite mixed. Further, the task paradigms and incentives used differed between studies and factors which may potentially affect the FRN have not yet been studied thoroughly.

3.2.2. Feedback-P3

So far, only three studies investigated the feedback-P3 in ASD patients, with two studies failing to find any significant group differences in feedback-P3 amplitudes between patients with ASD and NTs (Bellebaum et al., 2014; Larson et al., 2011). A third study conducted by Groen et al. (2008) also did not reveal significant group differences for the early period of the feedback-P3 (before 450 ms). However, the amplitude of the later interval of the feedback-P3 (500–700 ms) did yield significant group differences, such that the feedback-P3 amplitude was larger for the NC group as opposed to the ASD group (Cohen's $d = 0.42$). The authors suggested that altered late feedback-P3 amplitudes may reflect reduced affective responsiveness to negative feedback stimuli, resulting in less processing of negative feedback and thus reduced amplitudes. Inconsistent findings with regard to the feedback-P3 may be explained by differences in rewards. Groen et al. (2008) used points, whereas Larson et al. (2011) and Bellebaum et al. (2014) provided monetary rewards. It may have been the case that a non-monetary reward is less appealing or less salient to patients with ASD as compared to NTs, resulting in diminished amplitudes. In line with this notion is the finding that magnitude of reward has an influence on feedback-P3 amplitude (Yeung and Sanfey, 2004). No associations between feedback-P3 amplitudes and behavioral performance could be observed (Bellebaum et al., 2014) and none of the reviewed studies investigated whether IQ, age, or medication use had an effect on the amplitude of the feedback-P3. One study included five ASD patients taking antidepressant medication (Bellebaum et al., 2014), but did not control for potential effects on the feedback-P3.

3.3. Observational performance monitoring

So far, there are no studies investigating the oERN in individuals with ASD. However, two studies examined oERN amplitudes in ASD and revealed inconsistent findings (Bellebaum et al., 2014; Clawson et al., 2014). Whereas Clawson et al. (2014) reported no differences in oERN amplitudes for individuals with ASD and NTs (Cohen's $d = 0.26$), Bellebaum et al. (2014) did reveal significant reduced FRN amplitudes in ASD (irrespective of learning type and feedback valence; see

section on the FRN). Differences between studies may have contributed to the inconsistent findings. First, as pointed out previously, participants in the Bellebaum et al. (2014) study were mostly female and adults. Conversely, participants in the Clawson et al. (2014) study were mostly male and children or adolescents. Second, different cognitive paradigms were employed in the two studies; Bellebaum et al. (2014) used a probabilistic learning paradigm, whereas Clawson et al. (2014) used a variation to the Flanker task. It might have been the case that the probabilistic learning paradigm was too complex for individuals with ASD, compared to NTs, which resulted in less processing and therefore, smaller oFRNs. Third, Clawson et al. (2014) required their participants to internally count the number of errors committed by the partner they observed. This effortful dual task might have taken away resources for performance monitoring or alternatively, for concentrating on the task. Lastly, participants in the Clawson et al. (2014) study were seated in the same room as their partners while performing the study. In contrast, Bellebaum et al. (2014) placed participants and confederates in different rooms. Clawson et al. suggested that this might have affected the social and motivational aspects of the task, resulting in reduced oFRNs.

Studies also investigated potential moderators of oERN amplitude. Clawson et al. (2014) did not find any associations between medication use, age, ASD symptoms or anxiety and oERN amplitude. The amplitude of the oERN was also not related to reward type (participants either received the points the confederates earned or the confederates kept the points themselves). Furthermore, Bellebaum et al. (2014) reported that symptoms of depression or state empathy were not related to oERN amplitude.

4. Discussion

Almost 25 years after the discovery of the ERN, electrophysiological studies on performance monitoring in ASD are scarce. The number of available studies is still limited ($k = 9$ on internal performance monitoring, $k = 4$ on external performance monitoring, and $k = 2$ on observational performance monitoring) and studies are quite heterogeneous with regard to cognitive paradigms and sample characteristics. Nevertheless, the majority of studies point to reduced internal performance monitoring, as indexed by reduced ERN amplitudes. Evidence for reduced Pe amplitudes in ASD is mixed. Nevertheless, two out of six studies did reveal reduced Pe amplitudes, accompanied by medium to large effect sizes. More studies on the Pe in ASD are however needed in order to draw more definite conclusions. Inconsistencies with regard to internal performance monitoring studies are likely the result from a combination of factors including task difficulty, sample characteristics and problems with statistical power (see below for a more thorough discussion). Reduced ERN (and Pe) amplitudes are demonstrating impaired internal performance monitoring in ASD, in line with behavioral studies (Bogte et al., 2007; Russell and Jarrold, 1998). Although only few studies investigated performance monitoring ERPs in relation to empathy, one study found larger ERN amplitudes to be associated with higher ToM abilities in autism and NTs (Henderson et al., 2015). In combination with the observation that cognitive empathy is deficient in individuals with ASD (Dziobek et al., 2008; Rogers et al., 2007; Rueda et al., 2015; Schwenck et al., 2012), we hypothesize that diminished internal performance monitoring (as indexed by the ERN) aggravates empathy related deficits in ASD (see Table 3). ToM reasoning/cognitive empathy and internal performance monitoring both require the cognitive component of observing and evaluating abstract cues in order to adapt one's own behavior. It has indeed been noted that intact EF is necessary (although not sufficient) for ToM reasoning (Decety and Meyer, 2008; Mahy et al., 2014). So far, no study has directly investigated the relationship between the ERN and EF in ASD. However, a study with NTs revealed a significant association between EF and ERN amplitude (Larson and Clayson, 2011). Therefore, future studies should investigate the relation

between specific aspects of EF, ToM reasoning and the ERN in ASD (see Table 3).

Results of this review could not establish a consistent relation between performance monitoring and ASD symptom severity, as measured by total problem scores on ASD diagnostic tools. The most robust finding is that better social skills seem to be related to larger ERNs, which was found by three out of four studies investigating this relationship (Henderson et al., 2006; Santesso et al., 2011; South et al., 2010). Only Groen et al. (2008) could not establish such an association. The observation of generally larger ERNs in relation to better social skills in ASD are in line with the finding that in NT adults, difficulties in social behavior have been found to be associated with reduced ERNs (Dikman and Allen, 2000). Our review could not reveal associations between restrictive and repetitive patterns of behavior and ERN amplitude, as none of the studies explicitly explored this relationship. However, since restricted and repetitive patterns of behavior have strong diagnostic significance, their relation to the ERN may be further investigated. Future studies with the objective of investigating such a potential relationship are therefore of interest (see Table 3).

Unfortunately, most studies did not control for comorbidity or symptom presentation. For example, individuals with ASD often have internalizing problems or comorbid affective disorders, including anxiety and depression (Simonoff et al., 2008; Sukhodolsky et al., 2008). Negative affect seems to be related to enhanced ERNs (Hajcak et al., 2004), whereas some findings of the present review point to *reduced* ERNs in relation to ASD. Failures to control for comorbid symptoms or trait characteristics of participants may partly explain inconsistencies across studies. It is therefore desirable to investigate such a potential relationship further in order to identify which aspects of ASD cause the ERN to be reduced.

The few studies ($k = 4$) examining external performance monitoring point to intact FRN and feedback-P3 amplitudes in individuals with ASD. However, it should be noted that the majority of studies investigated the FRN by utilizing guessing games in which participants had to guess correct responses, and in which feedback valence was independent of performance. Therefore, the question arises to what extent these studies investigated actual performance monitoring. The FRN is likely to reflect a binary “good versus bad” evaluation of outcomes. It may therefore be the case that in reward-processing

paradigms, the motivational drive to receive rewards (where the only other option is to not receive anything) is intact in ASD. Interestingly, the single study reporting a difference between children with ASD and NTs with regard to FRN amplitude utilized a probabilistic learning paradigm in which correct responses had to be learned (Bellebaum et al., 2014). Thus, participants in this study had to adjust their behavior from rather abstract information. As already mentioned with regard to the ERN, individuals with ASD might have difficulties observing and evaluating abstract information and to make use of it for adapting their own behavior. Based on these findings, we hypothesize that reinforcement learning is impaired in ASD. This proposal is consistent with the finding that children with ASD have difficulty in generating abstract rules concerning stimulus–reward associations (Dawson et al., 2001; Jones et al., 2013). Only one study could reveal differences for feedback-P3 amplitudes between a group of ASD patients and NTs (Groen et al., 2008). This difference was, however, only evident for the later interval of the feedback-P3 and may index reduced affective responsiveness to negative feedback in ASD. Future studies should be conducted with the aim to replicate this finding. Although our review only found limited evidence for altered feedback-P3 amplitudes in ASD, this component may be particularly suitable for studying sensitivity for reward magnitude in reward-processing paradigms (Yeung and Sanfey, 2004).

Observational performance monitoring seems to be most directly connected to empathy (Thoma and Bellebaum, 2012), because it involves cognitive (understanding another person's mental state), as well as emotional (responding to another person's emotional state) components of empathy. However, an association between FRN amplitude and state or trait empathy scores could not be established (Bellebaum et al., 2014). Since only two studies – with contradicting findings – investigated the oFRN in ASD so far, it is not possible to draw general conclusions about the oFRN (and its relation to empathy) in ASD. In accordance with our suggestion that performance monitoring, which involves abstract feedback aimed at adjusting one's own behavior, may be impaired in ASD, we hypothesize that observational performance monitoring is deficient in ASD – when information gained through observation should be used to guide one's own behavior. Simple observation, without the goal of behavioral adjustment or learning, may be unaffected.

Table 3

Hypotheses and suggestions for future performance monitoring studies in ASD based on findings of the current review.

Hypotheses	Possible approaches for testing hypotheses
1. Diminished internal performance monitoring (as indexed by the ERN) aggravates empathy related deficits in ASD	Relate (cognitive) empathy scores to internal performance monitoring ERP components
2. Reinforcement learning is impaired in ASD	Regression analyses may be more powerful than group comparisons Employ a cognitive paradigm in which performance feedback facilitates learning (e.g. probabilistic learning paradigm with only or mostly informative feedback) Appealing and age appropriate rewards should be provided
3. Observational performance monitoring is deficient in ASD – when information gained through observation should be used to guide one's own behavior.	Compare observational performance monitoring ERPs for situations when observations can be used to guide one's own behavior versus situations when observations are not useful for guiding one's own behavior in one study
Open questions	Possible approaches for testing
Is there a relation between EF, ToM reasoning and ERN amplitude in ASD?	Correlational/regression analyses
Which aspects of ASD cause the ERN to be reduced?/What role do comorbid symptoms play?	Group patients according to their symptom presentation; investigate comorbid disorders
Is external performance monitoring involving abstract feedback reduced in ASD, while external performance monitoring involving concrete, salient feedback is intact?	Test participants in both conditions
Does the generally reduced ERN in ASD reflect developmental delay or developmental deviance?	Longitudinal study
Is there an association between restrictive and repetitive patterns of behavior and ERN amplitude?	Group comparisons between ASD patients with high problem scores of restrictive and repetitive pattern of behavior and ASD patients with low problem scores on restrictive and repetitive pattern of behavior (and a normal control group) Correlational/regression analyses
Which interventions can normalize performance monitoring in ASD?	Intervention studies, including behavioral therapeutic interventions (motivational incentives), neurobehavioral therapies, and psychopharmacological treatment

Note. ASD = autism spectrum disorder; ERN = error-related negativity; ERP = event-related potential; EF = executive functioning; ToM = theory of mind.

4.1. Limitations and future directions

Some limitations of the examined studies and the review itself should be noted. First, sample sizes of the reviewed studies were rather small. For detecting a medium effect size ($f = 0.25$) in the most commonly employed design of the studies included in this review (a within-between group interaction in a repeated measures ANOVA with 2 groups and one within-subjects variable), 17 participants are needed per group (with a power of 0.80 and an alpha of 0.05). More participants are needed when using more complex designs, when using simple *t*-tests, or when group differences are small. Five of the reviewed studies included <17 participants per group. Future studies should therefore include larger sample sizes in order to find effects of a magnitude large enough to be practically meaningful and to be generalizable to the population. Second, age ranges of participants should be decreased in future studies. Larger ERNs are associated with development, such that the ERN increases from early childhood to young adulthood (Ladouceur et al., 2007; Santesso and Segalowitz, 2008; Tamnes et al., 2013). The finding of generally reduced ERN amplitudes in children with ASD might indicate developmental delay of brain-processes mediated by the prefrontal cortex. However, one ERN study found reduced ERN amplitudes also in adults, suggesting permanent deficits (Santesso et al., 2011). This is in line with the notion that developmental trajectories may be deviant in ASD (Shaw et al., 2010). Either way, using large age ranges may have obscured finding significant differences in ERN amplitudes between ASD and NTs (for example, in the study conducted by Henderson et al., 2006). A further limitation of the reviewed studies is that studies only included participants with high-functioning ASD. Conclusions are, therefore, limited to the high-functioning ASD population and may not extend to more severe forms of ASD.

The results of our review indicate that, in addition to age, error rates, ToM abilities, social skills and internalizing problems may affect ERN amplitude in ASD. Furthermore, performance monitoring ERPs are influenced by a variety of additional factors, such as motivation, personality, and psychopathology (Olvet et al., 2010; Vaidyanathan et al., 2012). Furthermore, results of our review suggest that task complexity or task difficulty may affect performance monitoring ERPs. More difficult tasks, such as the probabilistic learning paradigm used by Groen et al. (2008), require more effort, which in turn may lead to relatively enhanced ERNs. Indeed, it has been shown that different cognitive paradigms demonstrate differences in ERN and Pe amplitudes, possibly related to task difficulty (Riesel et al., 2013). Future studies should carefully examine and consider potential confounding factors discussed above. Moreover, the studies included in this review used different methods of measuring the ERN. Original reports on the ERN appear to treat the difference between correct and incorrect trials as the main variable of interest (Falkenstein et al., 1990; Hohnsbein et al., 1991), and a small negativity seems to be present after correct trials as well (Vidal et al., 2000), indicating generic comparison processes. Therefore, future studies should not treat the amplitude of error trials only as the variable of interest, but rather the difference wave between correct and incorrect trials. Further, the different studies included in this review used different cut-off scores for the diagnostic instruments/tools for symptom assessment. For example, Henderson et al. (2015) used a cut-off score of 12 for the SCQ, but report scores on the SCQ for their patient sample ranged from 9 to 33. In contrast, Groen et al. (2008) used a cut-off score of 15. Future research should adhere to stricter research guidelines by using cut-off scores as indicated in the literature, such that patient groups are better defined and future comparison across studies becomes more justified.

A limitation of the present review is that we compared studies using different age groups. As mentioned before, especially ERN amplitudes change with age. Comparing different age groups is therefore not advisable. However, due to the scarcity of studies investigating performance monitoring ERP-components in ASD, we decided to include studies

using a range of different age groups. Furthermore, we compared results of different cognitive paradigms. Especially the Pe – but not the ERN – is affected by task characteristics (Overbeek et al., 2005). For example, the Pe is larger in a Flanker task compared to a source memory task. Moreover, it should be noted that altered ERN amplitudes are not specific to ASD. Several other (neuro-) psychiatric disorders (e.g. ADHD and schizophrenia) have been associated with reduced ERN amplitudes (see Manocha and Agam, 2013; Ullsperger, 2006 for reviews). Reduced ERN amplitudes can thus not be considered as an index for ASD, but merely as a neurocognitive trait that is more likely to be present in ASD but also in other disorders. However, studying performance monitoring ERPs in ASD may shed light on the neurocognitive mechanisms in ASD and their associations to overt symptoms.

Future research should address open research questions with regard to performance monitoring in ASD. Hypotheses and suggestions for future research as well as possible ways of testing them are summarized in Table 3. In general, more research should be carried out on observational performance monitoring. Observing and evaluating other people's behavior is crucial for successful goal-directed social behavior. Since individuals with ASD are likely to have problems in this function, research on observational performance monitoring may give rise to social problems associated with ASD. Furthermore, it remains unknown what exact symptoms or deficits of patients with ASD cause the ERN to be reduced. Future research with well-defined patient groups is needed to get a clearer picture of the relationship between ASD symptomatology and performance monitoring.

Lastly, research should focus on interventions that may normalize reduced internal performance monitoring in ASD. Individuals with ASD might benefit from external, concrete feedback on their performance, which may stimulate reinforcement learning and consequently internal performance monitoring (see also Hypothesis 2 in Table 2). Especially the use of motivational incentives with performance feedback, such as material rewards and response costs, might normalize internal performance monitoring, as was for example demonstrated in children with attention deficit hyperactivity disorder (Groom et al., 2010; Rosch and Hawk, 2013). Also psychopharmacological treatments with compounds that influence the dopamine system, such as methylphenidate, have been shown to enhance internal performance monitoring (De Bruijn et al., 2004; Hester et al., 2012). Lastly, individuals suffering from reduced internal performance monitoring, regardless of their type of psychopathology, might benefit from neurobehavioral therapies that are targeted specifically towards improving cognitive control (Siegle et al., 2007).

5. Conclusion

Research on performance monitoring in ASD is in its infancy with, so far, only small and heterogeneous studies. Nevertheless, it appears that individuals with ASD have problems with internal performance monitoring and with learning from external, abstract feedback. In contrast, the processing of external, concrete feedback may be largely intact in ASD. Neurocognitive deficits in performance monitoring may aggravate autism-related symptoms, such as problems with cognitive empathy and social skills. Future studies are needed to validate these results and to test the hypotheses raised in the Discussion. For this purpose, ERPs are especially useful due to their high reliability.

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