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The Impact of Error Awareness on Error-Related Negativity: A Review and Meta-Analysis

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Abstract

In this systematic review and meta-analysis, the relationship between error awareness and the amplitude of Error-Related Negativity (ERN), a neural response to errors associated with cognitive control and error monitoring processes, was examined. Five studies published between 2010 and 2020, involving a total of 302 participants, were analyzed. Findings revealed a more pronounced negative amplitude of the ERN for aware errors compared to unaware errors, supporting the Error Detection Theory and Reinforcement Learning Theory. The results did not directly support or contradict the Conflict-Monitoring Theory. These findings underscore the critical role of conscious error detection in modulating ERN responses and adaptive behavioral modifications. However, due to the limited number of included studies and variability in their methodologies, caution is needed in interpreting the results. Future research should aim to validate these findings with larger samples and standardized study designs, while also exploring a more nuanced understanding of error awareness.

[Keywords: error-related negativity, error awareness, error monitoring]

The impact of error awareness on error-related negativity: A Review and Meta-Analysis

Introduction

Every day, our brains constantly make split-second decisions and adjustments as we navigate our lives. Whether touching a hot stove and quickly pulling our hand away or accidentally taking a wrong turn and correcting our route, these are all instances of error monitoring. Error monitoring refers to the neural processes of detecting and responding to errors during cognitive and behavioral tasks, a fundamental aspect of our daily functioning.

In a more specific context, error monitoring is critical in adaptive behavior, which refers to the brain's ability to adjust its actions and responses based on environmental feedback. For example, a basketball player learns to adjust the angle and force of their throws based on previously missed shots, an instance of adaptive behavior in action.

Similarly, error monitoring is integral to performance monitoring, which is how the brain evaluates its actions and outcomes to adjust future operations. Comparable to a student refining their study strategies based on the feedback received from their grades. Performance monitoring is crucial for learning, allowing the brain to identify and correct errors, thereby refining its strategies over time.

Several decades of research have shown the capacity of our brain to detect performance errors without the necessity for external feedback and conscious awareness of the committed errors (Ullsperger et al., 2010). Since the 1960s, behavioral studies on detecting errors in reaction time (RT) tasks revealed a fast and automatic error correction response after committed errors. This response was faster than the awareness of the error, which points to covert error-detection processes (Yeung et al., 2004). In the early 1990s, error detection was investigated through electrophysiological studies and event-related potentials (ERPs). One error-related component has been found repeatedly: the error-related negativity (ERN). This electrophysiological index is now acknowledged as a fundamental component of error monitoring (Dehaene, 2018; Falkenstein et al., 2000; Nieuwenhuis et al., 2001).

What is the ERN?

The ERN is a negative response-locked ERP associated with erroneous responses in behavioral tasks (e.g., Flanker, Stroop, go-NoGo tasks) that peaks within 100 ms post-response (Bush et al., 2000).

The exact causes of the ERN are still not fully understood, and there is neither any agreement on the neurobiological origin of the ERN nor other error-related components. The current literature does not state if they share the same neural generators and whether they are from distinct neural processes or originate in similar processes. Both neuroimaging- and neuropsychological studies suggest that the anterior cingulate cortex (ACC) and lateral prefrontal cortex (lPFC) are involved in error processing (Bush, 2000; Gehring & Knight, 2000). Other regions, such as the insula (Ullsperger, 2010) and basal ganglia (Holroyd & Coles, 2002), also contribute to error processing mechanisms.

Several brain regions are involved in error detection, and evidence suggests injuries outside of the ACC may have a distal influence, possibly by altering modulatory effects. The ERN is rendered less sensitive to errors and is compromised by lesions in the basal ganglia (Ullsperger & Von Cramon, 2006) and damage to the lPFC (Brazdil et al., 2002). Furthermore, white matter-only frontal lobe lesions are sufficient to produce equivalent outcomes (Turken & Swick, 2008). As a result, it would seem that connections between different frontal areas are essential for generating ERN and performance monitoring in general.

Research has also shown that the ERN is altered in individuals with various neurological and psychiatric conditions, such as anxiety (Banica et al., 2020; Moser et al., 2013), obsessive-compulsive disorder (OCD) (Gehring et al., 2000; Riesel, 2019; Xiao et al., 2011), and narcissism (Mück et al., 2023). These findings suggest that the ERN may be a valuable tool for researchers to gain insights into the underlying neural mechanisms of these disorders. This information can help guide the development of more effective treatments and interventions for individuals with these conditions.

Theories of ERN Elicitation

Several theoretical frameworks have been proposed to explain the generation of the ERN, each providing unique insights into the brain's error detection and processing mechanisms.

First, the Error Detection Theory suggests that the ERN is generated when there is a discrepancy between a given action's predicted and actual outcomes (Bush et al., 2000; Falkenstein et al., 1991). This theory posits that the brain anticipates a specific event, and if the actual outcome differs, the ERN is triggered, signaling an error.

Building on this idea, the Reinforcement Learning Theory introduces a novel perspective, suggesting that a dopaminergic system, critical to reinforcement learning and operating within the parameters of learned expectancies, instigates the ERN (Holroyd & Coles, 2002). In essence, this theory integrates the basic premise of error detection with neurophysiological concepts of learning and expectancy.

Lastly, the Conflict-Monitoring Theory offers a different view, proposing that the ERN is the product of a conflict-monitoring mechanism within the brain, which identifies inconsistencies between different response options (Botvinick et al., 2001; Yeung et al., 2004).

According to this perspective, the ERN does not necessarily signify an error occurrence but rather indicates the level of conflict between competing responses.

Influences on the ERN

Thus far, there have been several findings in studies pointing at multiple factors that seem to influence the amplitude of the ERN. One consistent finding that influences the amplitude of the ERN is when accuracy is prioritized over speed in behavioral tasks. The ERN amplitudes tend to be bigger than when speed is prioritized over accuracy. Higher levels of motivational salience of errors also enhance the ERN (Gehring et al., 2018).

Other findings, such as error awareness and its influence on error processing, do not show a consistent pattern. For instance, in an influential study from 2001, an anti-saccade task (AST) was performed to explore this relationship. The AST is a cognitive task where participants are instructed to look in the opposite direction of a visually presented stimulus, requiring cognitive control to suppress the natural response of looking toward the stimulus. In this specific AST study, the ERN amplitude did not differ between aware and unaware errors (Nieuwenhuis, 2001).

Subsequently, in 2012, a systematic review of the first decade of research on error awareness and the ERN compiled a considerable body of studies. Contrary to previous beliefs, these studies suggested that the ERN is indeed influenced by error awareness, showing larger ERN amplitudes for aware errors than for unaware errors (Wessel, 2012).

This systematic review and meta-analysis will evaluate study results on error awareness and the ERN in studies conducted during the second decade of evidence (2010-2020).

Different Studies, Different Findings?

Task paradigm designs can influence the ERN and error awareness in several ways. The task's difficulty, the type of response required, and the presence and absence of feedback and reward can influence the ERN's amplitude and degree of error awareness. It is possible that participants are more aware of their errors when these factors come into play.

The choice of electrode reference in an EEG study can significantly impact the amplitude and latency of error-related ERPs. This choice influences the interpretation of voltage differences between electrodes on the scalp and, consequently, the outcomes of the study (Klawohn et al., 2020; Sandre et al., 2020). While there are several typical EEG reference schemes, the choice of electrode reference will be the primary focus of this study. It is important to note that while the choice of electrode reference can significantly influence the study's results, other EEG-related parameters, such as the overall EEG scheme, electrode location, filtering, baseline correction, and time-frequency analysis, also play substantial roles. However, these aspects fall outside the scope of this study and will not be discussed in detail.

Error awareness

The conscious perception of errors, as defined in this paper, refers to a state of being access conscious (aware), which implies that the content of such a state is available for a verbal report (Wessel, 2012). Reportability differentiates aware from unaware errors, specifically whether or not the subject can report the inaccuracy of their response. This aspect of error awareness introduces a significant challenge in ERN research. It is not always straightforward to discern between what constitutes an 'aware' and an 'unaware' error based on subjective reports. This issue further complicates our understanding of the relationship between error awareness and ERN amplitudes, making it a critical area of focus in the field.

One question arises about what degree of awareness a subject can report after making an erroneous response in a behavioral task and how that perceived degree of awareness affects the recorded ERN. For example, studies use different ways of measuring the degree of error awareness (i.e., how aware one is of their error). Some studies use a binary measurement system such as a button (press if ‘aware’/’unaware’ of their error) when the subject perceives their inaccuracy. A problem with a binary system such as this is that it might instruct the subject to press the button only when they are sure of having made an error and thus disregards all cases to what extent the subject is uncertain. Other studies use a graded system, such as a Likert scale, which might assess the degree of awareness in a more quantifiable manner.

With different ways of reporting aware and unaware errors, it is unsurprising that studies yield different results on the ERN and error awareness. Thus, it is difficult to determine how aware a person has been during testing and whether subjective awareness has affected the ERN.

Review and meta-analysis aim

Through a systematic review and meta-analysis, this paper aims to scrutinize the findings of studies from the recent decade of evidence regarding the impact of error awareness on the ERN observed in EEG studies involving diverse task paradigms and other study design factors.

While the ERN can provide insight into the mechanisms underlying self-awareness and metacognition, this meta-analysis focuses on the relationship between error awareness and the magnitude of the ERN. This analysis will strive to resolve the existing discrepancies in the literature and clarify how the conscious perception of errors influences this electrophysiological marker of performance monitoring. Doing so aims to contribute to our understanding of the cognitive processes underlying error monitoring and the potential implications for metacognitive abilities and consciousness. The ultimate goal of this paper is to provide a more comprehensive and nuanced understanding of the relationship between error awareness, performance monitoring, and the ERN.

Methods

Search strategy

In March 2023, a comprehensive literature search was conducted on electronic databases - Web of Science, Scopus, and PubMed. The search included articles published from 2010 to 2020, resulting in 58, 84, and 106 studies, respectively. Based on prior studies on error-related ERPs and error awareness, search terms included (ERN OR "error-related" OR "error related" OR "error negativity") AND (unaware OR aware OR conscious), within the title, abstract, and keyword fields.

The search results were exported to a Google Spreadsheet to identify and remove duplicates, with some duplicates manually eliminated due to minor title variations. Subsequently, titles and abstracts were screened for eligibility, and the remaining articles were evaluated based on a full-text reading. See Figure 1 for the PRISMA flow diagram.

Two reviewers independently conducted the study selection, evaluation, and data extraction. Discrepancies were addressed through consensus; the study was excluded if no agreement was reached.

Inclusion & exclusion criteria

For this systematic review and meta-analysis, the selection of studies adhered to specific inclusion and exclusion criteria. For inclusion, studies needed to be peer-reviewed, written in English, and published between January 2010 to December 2020. The studies should have involved adult human participants, irrespective of their clinical status. Additionally, these studies needed to employ ERP techniques within tasks related to cognitive control or performance monitoring. Crucially, studies should have reported on error awareness by quantifying ERN amplitude and provided these measurements under error awareness and unawareness conditions. Conversely, articles were excluded if they were not original research articles, such as reviews, editorials, book chapters, or conference papers, and were not written in English.

Data extraction

Data were extracted from each qualified study, including information about the article (e.g., authors, publication year), the population (e.g., sample size, age, and gender distribution), the study design (e.g., task paradigm, subjective error awareness reporting), and methodological choices (e.g., electrode reference, time windows defining ERP components of interest). Mean ERN amplitude values for aware and unaware errors were extracted from each study. Relevant statistics (e.g., means and standard deviations (SDs), t-values, p-values, standard errors) were utilized to compute the effect size using Cohen's d. If the study lacked sufficient data for computing mean amplitude differences or effect sizes, it was incorporated into a qualitative discussion or considered for secondary analysis.

Statistical methods

The statistical analysis was conducted using Jamovi statistical software (version 2.3.21.0). The meta-analysis framework encompassed two main components: a main meta-analysis of the included studies and additional exploratory analyses.

In the main meta-analysis, a random-effects model following the Hunter & Schmidt approach (Schmidt & Hunter, 2014) was used to synthesize the findings from the eligible studies and explore the differences in ERN amplitudes between aware and unaware errors. An alpha level of .05 was set for all statistical tests to determine significance. The effect size measure was Cohen's d, which represents the magnitude of the difference in ERN amplitudes between aware and unaware errors, normalized by the pooled standard deviation. Effect sizes were calculated from means and standard deviations or other relevant statistics (e.g., t-values, p-values, standard errors) extracted from each study. If standard errors (SE) were reported, they were converted to standard deviations using the formula: $SD = SE * \sqrt{n}$, where SD is the standard deviation, and $\sqrt{n}$ is the square root of the sample size.

The estimated average standardized mean difference (SMD) and its corresponding 95% confidence interval (CI) were calculated using the method of moments estimator. Heterogeneity across the included studies was evaluated using the Q-test and I^2 statistic. Outliers and influential studies were examined to ensure the robustness of the results. Publication bias was assessed using both the Begg and Mazumdar Rank Correlation and Egger's regression tests. These tests were chosen as they each measure publication bias in slightly different ways, providing a more comprehensive assessment. The Begg and Mazumdar test investigates correlation between the ranks of effect sizes and the ranks of their variances, which can help detect bias related to sample size. On the other hand, Egger's regression test assesses the relationship between the effect size and the standard error, which can indicate bias arising from factors such as study precision.

Outliers and influential studies were identified using studentized residuals and Cook's distance. A study was considered an outlier if its studentized residual value exceeded ± 2.6383, an extreme value provided by the meta-analysis package MAJOR in Jamovi software (version 2.3.21.0) for identifying potential outliers. Studies with high Cook's distance values were considered potentially influential.

Exploratory analyses were conducted to determine the influence of electrode reference and paradigm choice on mean ERN amplitudes for aware and unaware errors. A two-way factorial analysis of variance (ANOVA) was carried out using the available data from the included studies, which allowed for the examination of the main effects and interaction of electrode reference and paradigm choice on the mean amplitudes for aware and unaware errors.

Results

Characteristics of Included Studies

In total, 248 articles were initially identified from the literature search across Web of Science, Scopus, and PubMed. After removing duplicates, 152 articles remained for the title and abstract screening. From these, 72 articles were deemed eligible for full-text review. Following the full-text review, nine studies were initially deemed eligible for inclusion in the meta-analysis. However, upon further inspection, four studies were needed to provide the necessary data, such as standard deviations or other required information. Therefore, only five studies were included in the final meta-analysis.

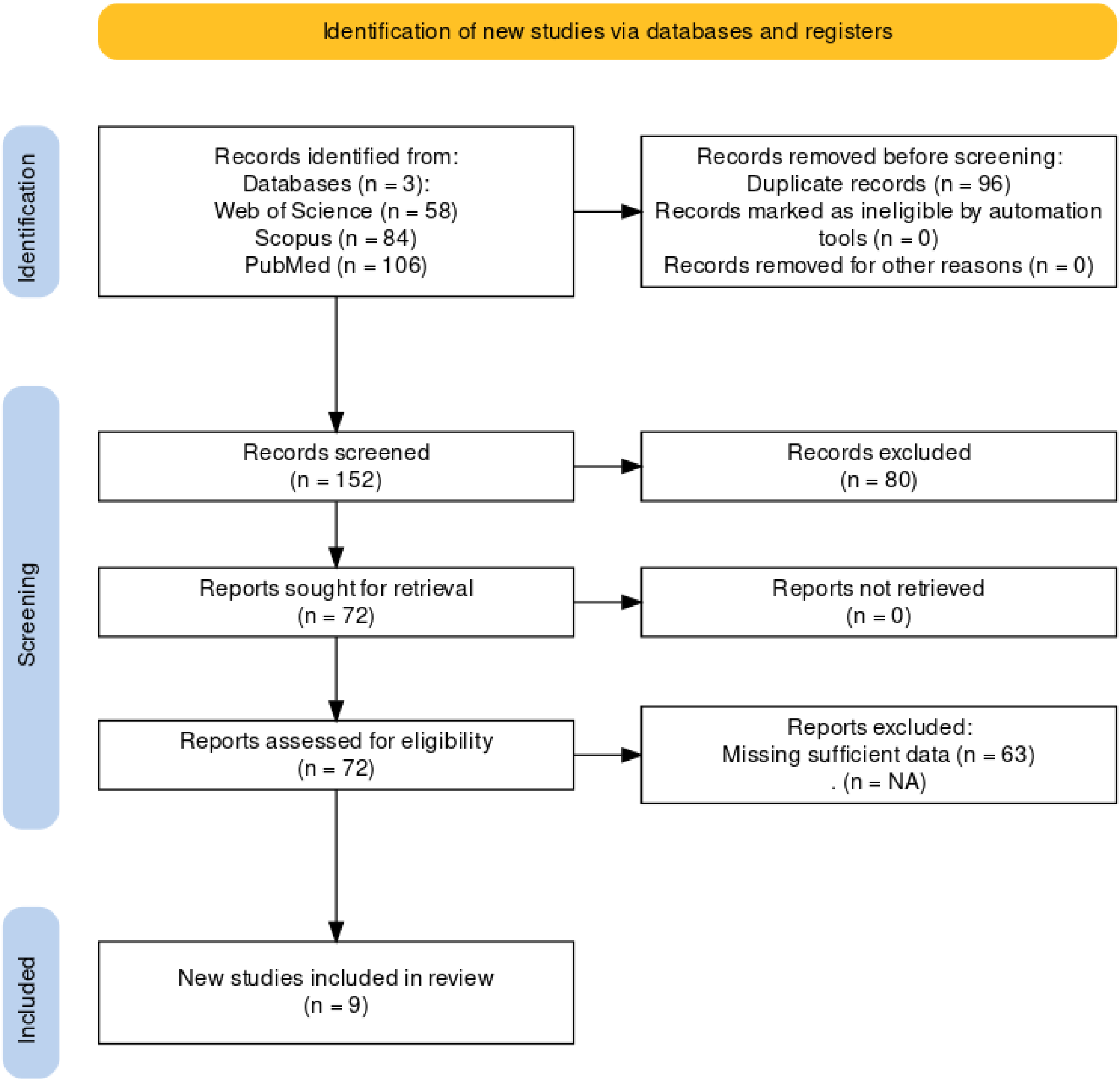
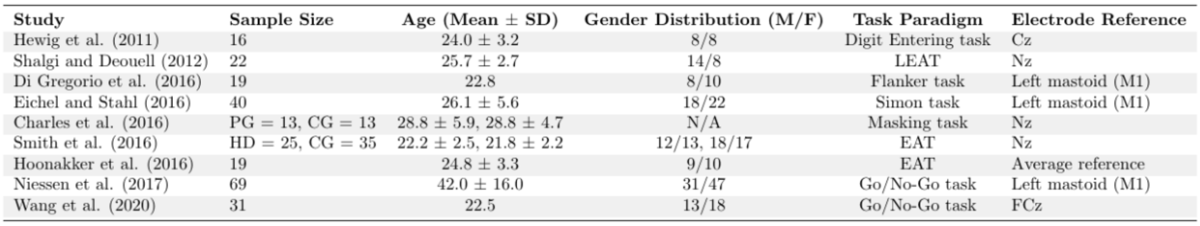


Figure 1. PRISMA flow chart depicting article selection (Haddaway et al., 2022).

Out of the nine included studies, only five provided amplitude means and standard deviations. The remaining four provided amplitude means that were extracted from the original articles, a process that will be described in further detail later in the text. Despite the lack of complete data, these studies still held value for secondary analysis or qualitative discussion. They contributed essential information regarding ERN amplitude differences between aware and unaware errors.

The nine included studies had a combined total of 302 participants after excluding participants who did not meet the eligibility criteria. Detailed demographic information, such as mean age and gender distribution, for each study, is provided in Table 1. Most of the studies (7/9) employed healthy adult participants, while two investigated clinical populations (one focused on individuals with schizophrenia, and the other on patients classified as heavy alcoholic drinkers).

The studies included in this analysis had sample sizes ranging from 16 to 69 participants. Across these studies, various cognitive control tasks such as the Simon, Flanker, and Go/No-Go tasks were employed. These paradigms are notable for their relevance, as they induce cognitive processes closely related to error monitoring and cognitive control. All studies utilized subjective reports to measure error awareness. This approach offered a perspective on the participants' conscious recognition of their errors. Despite a shared focus, the methodological approaches varied across studies. This diversity was reflected in the choice of cognitive control tasks, the techniques for measuring error awareness, and the type of EEG reference electrodes used in the recordings.



Study	Sample Size	Age (Mean ± SD)	Gender Distribution (M/F)	Task Paradigm	Electrode Reference
Hewig et al. (2011)	16	24.0 ± 3.2	8/8	Digit Entering task	Cz
Shalgi and Deouell (2012)	22	25.7 ± 2.7	14/8	LEAT	Nz
Di Gregorio et al. (2016)	19	22.8	8/10	Flanker task	Left mastoid (M1)
Eichel and Stahl (2016)	40	26.1 ± 5.6	18/22	Simon task	Left mastoid (M1)
Charles et al. (2016)	PG = 13, CG = 13	28.8 ± 5.9, 28.8 ± 4.7	N/A	Masking task	Nz
Smith et al. (2016)	HD = 25, CG = 35	22.2 ± 2.5, 21.8 ± 2.2	12/13, 18/17	EAT	Nz
Hoonakker et al. (2016)	19	24.8 ± 3.3	9/10	EAT	Average reference
Niessen et al. (2017)	69	42.0 ± 16.0	31/47	Go/No-Go task	Left mastoid (M1)
Wang et al. (2020)	31	22.5	13/18	Go/No-Go task	FCz

Table 1. Characteristics of the Studies Included. * PG = Patient group, HD = Heavy Drinkers,

CG = Control group, , EAT = Error Awareness Task, LEAT = Lateralized Error Awareness Task

Main Findings

A random-effects meta-analysis was carried out to examine the standardized mean difference between aware and unaware errors in ERN amplitudes. Five studies were incorporated into the meta-analysis, one of which conducted two separate experiments with different groups of participants. Thus, the analysis effectively evaluated six experiments, even though they came from five individual studies.

The random-effects model computed an estimated average standardized mean difference of -0.2620, 95% CI [-0.4504, -0.0735], indicating a more negative ERN amplitude for aware errors relative to unaware errors (z = -2.7242, p = .0064). The p-value, which is less than the predetermined alpha level, confirms statistical significance. Most of the included studies reported negative effect sizes, corroborating this finding.

The heterogeneity analysis did not reveal any significant variability in the true outcomes ($Q(5) = 3.4596$, $p = .6295$, $\tau^2 = 0.0000$, $I^2 = 0.0000\%$), implying that the difference in ERN amplitudes between aware and unaware errors was consistent across the studies. An examination for outliers and influential studies, based on studentized residuals and Cook's distances, indicated that no studies exceeded the predefined thresholds. Specifically, no studies exhibited studentized residual values that could be classified as extreme (± 2.6383), indicating the absence of outliers in the model. According to Cook's distances, none of the studies were considered overly influential, further confirming the robustness of the meta-analysis findings.

A forest plot was constructed to visualize the effect sizes and their variance across the studies (Figure 2). This plot demonstrates the effect sizes from each study (Cohen's d) and their corresponding confidence intervals. The diamond at the base of the forest plot represents the overall effect size estimate from the random-effects model, signifying a more pronounced negative amplitude of the ERN for aware errors as compared to unaware errors (*SMD* = -0.2620, 95% CI [-0.4504, -0.0735]).

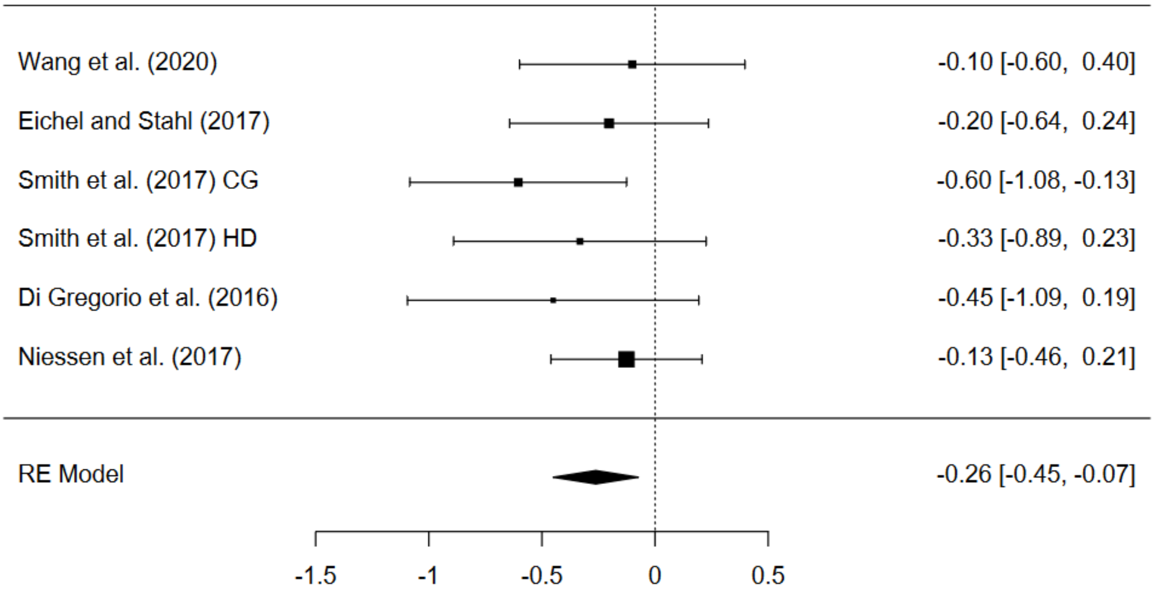


Figure 2. Forest plot. * CG = Control Group, HD = Heavy Drinkers

The potential for publication bias was assessed using the Begg and Mazumdar Rank Correlation test and Egger's regression test, which showed no evidence of funnel plot asymmetry or publication bias (*p* = .272 and *p* = .304, respectively). A funnel plot was generated to provide a visual confirmation of this (Figure 3). The symmetric distribution of the data points within the funnel plot suggests an absence of publication bias.

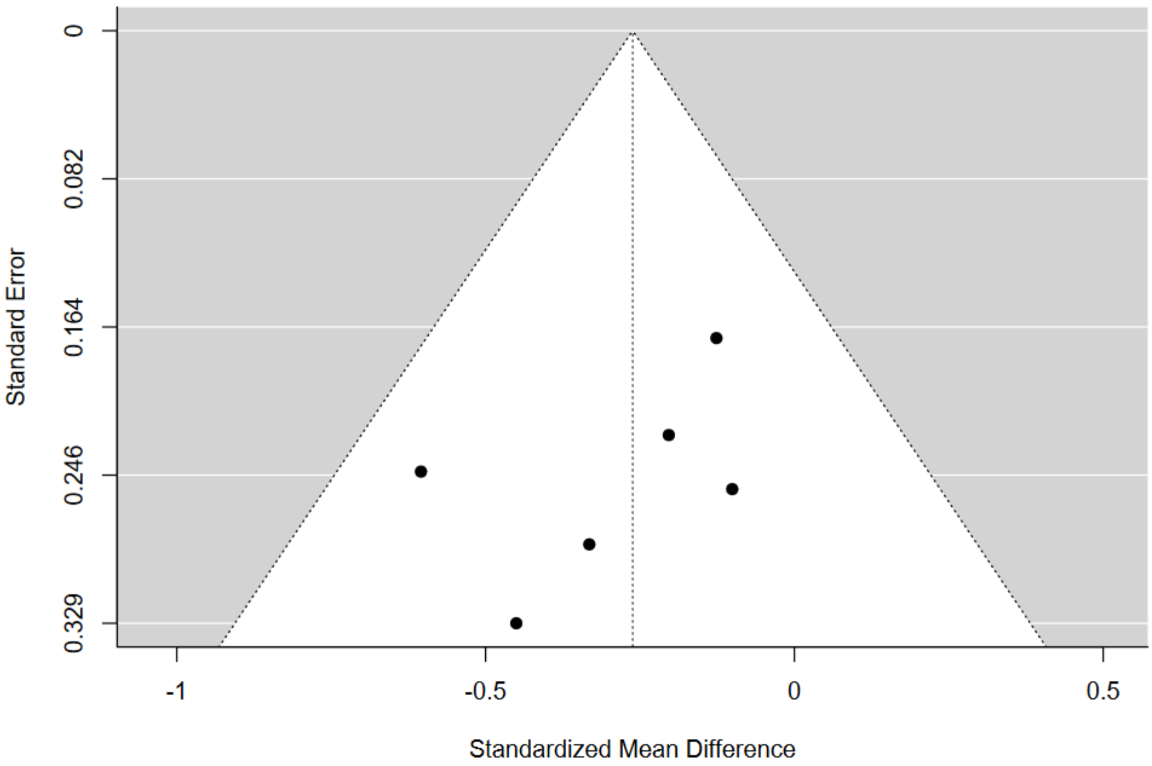


Figure 3. Funnel plot.

In summary, the analysis of the five independent data sources in this meta-analysis provides strong evidence that ERN amplitudes for aware errors are more negative compared to those for unaware errors. The forest and funnel plots further support this conclusion by providing a comprehensive overview of the effect sizes and publication bias assessment.

Additional exploratory analyses

Further exploratory analyses were carried out to scrutinize the impact of distinct factors on mean ERN amplitudes. These analyses incorporated four studies that did not provide standard deviations for the meta-analysis but offered mean amplitudes. In two of these studies, there were two groups, thus leading to a total of 12 data points for the exploratory analyses.

For the additional six data points, the mean amplitudes for aware and unaware errors were extracted from the graphs in the original articles using WebPlotDigitizer (version 4.6). These data points were subsequently included in the ANOVA analyses, along with the five studies that provided complete data for the meta-analysis.

For each type of error (aware and unaware), a two-way (factorial) ANOVA was performed separately to examine the main effects of electrode reference and paradigm choice on the mean amplitudes. This analysis considered 12 data points from the nine studies (six from the main meta-analysis and six additional data points from the exploratory analyses).

In conducting these analyses, it is important to note that there were differences in the amount of available data for the two independent variables, electrode reference and paradigm choice. Specifically, 10 data points included information on the electrode reference. However, only eight of these provided information about the paradigm choice used in the respective study. This resulted in a lower number of observations when analyzing the effect of paradigm choice compared to the electrode reference.

The ANOVA results did not reveal a significant main effect of electrode reference on mean amplitudes for either aware errors, ($F(4, 10) = 0.393$, $p = .808$), or unaware errors, ($F(4, 10) = 0.220$, $p = .919$). These findings suggest that electrode reference choice did not significantly influence the mean amplitudes for aware and unaware errors.

Likewise, there was no significant main effect of paradigm choice on mean amplitudes for aware errors, ($F(6, 8) = 0.999$, $p = .511$), or unaware errors, ($F(6, 8) = 1.17$, $p = .440$). These results indicate that paradigm choice did not significantly affect the mean amplitudes for either aware or unaware errors.

Discussion

Summary of Findings

This study deepens our understanding of the relationship between error awareness and ERN amplitudes, enriching current knowledge on error monitoring and cognitive control processes. The meta-analysis, performed on the evaluated studies, revealed a consistent pattern of a more pronounced negative amplitude of ERN for aware errors compared to unaware errors. This aligns with existing research, further emphasizing the critical role of error awareness in modulating neural responses to errors and enhancing cognitive control.

Theoretical Implications

The results of the current work support both the Error Detection Theory (Bush et al., 2000; Falkenstein et al., 1991) and the Reinforcement Learning Theory (Holroyd & Coles, 2002). Notably, the enhanced negative amplitude of the ERN for aware errors indicates that conscious recognition of an error triggers a discrepancy between predicted and actual outcomes, stimulating the enhanced negative amplitude of the ERN. This interpretation aligns with clinical observations in disorders like anxiety where anticipatory mechanisms may be disrupted (Banica et al., 2020; Moser et al., 2013).

While this study primarily investigates the relationship between error awareness and ERN amplitude, it is noteworthy to mention that ERN responses can occur even in the absence of error awareness. Prior research has illustrated that ERN can be elicited during trials where individuals were not consciously aware of committing an error (Nieuwenhuis et al., 2001). This suggests that the generation of ERN may not be strictly dependent on conscious error recognition but instead implies that conscious awareness of an error intensifies an existing ERN response. These findings underline the complexity of the neural mechanisms underlying error monitoring and highlight that ERN is not exclusively driven by conscious error detection but might also be influenced by subconscious error-related processes.

Furthermore, the findings imply that error awareness boosts the allocation of cognitive resources toward error processing, thereby increasing the efficiency of error correction. This idea resonates with the Reinforcement Learning Theory, wherein the possible activation of a dopaminergic system for reinforcement learning upon the conscious detection of an error could lead to improved learning from mistakes. Notably, this theory becomes particularly relevant when considering disorders like Parkinson's disease, schizophrenia, and attention-deficit/hyperactivity disorder (ADHD), which are associated with alterations in the dopaminergic system (Falkenstein et al., 2001; Holroyd & Coles, 2002; Mathalon et al., 2002; Sergeant et al., 2003). Damage to this system, as seen in these disorders, could affect reinforcement learning and thereby influence the ERN amplitudes. Therefore, understanding the ERN in the context of error awareness could offer valuable insights into the cognitive processes involved in these disorders.

As for the Conflict-Monitoring Theory, which proposes that the ERN is a reflection of the level of conflict between competing responses (Botvinick et al., 2001; Yeung et al., 2004), it may be relevant in conditions like OCD, where internal conflicts are prevalent (Gehring et al., 2000; Riesel, 2019; Xiao et al., 2011). The findings from this study neither confirm nor directly challenge this theory, yet the potential role of conscious error detection in resolving conflicts, thereby indirectly contributing to ERN generation, warrants further investigation.

The examination of these theories through the lens of this study not only provides deeper insights into the function of error awareness but also paves the way for understanding the wider implications of error monitoring and cognitive control processes.

Beyond these specific theoretical and clinical insights, the current work underscores the significant influence of conscious error detection on performance monitoring and the generation of the ERN. It emphasizes the complex role of error awareness in modulating ERN responses, revealing the necessity for more nuanced and reliable measures of error awareness. Furthermore, it highlights the potential for interventions designed to enhance error awareness in improving cognitive control in clinical populations, thus offering promising avenues for future research.

Consistent with prior research, the findings of the current study highlight the crucial roles of certain brain regions, such as the ACC, lPFC, insula, and basal ganglia, in error processing (Bush, 2000; Gehring & Knight, 2000; Ullsperger, 2010; Holroyd & Coles, 2002). Furthermore, the study reveals that damage to these regions, particularly the ACC, lPFC, and basal ganglia, can diminish the ERN's responsiveness to errors (Ullsperger & Von Cramon, 2006; Brazdil et al., 2002; Turken & Swick, 2008). This observation emphasizes the importance of understanding the interactions among these different frontal brain regions in the generation of ERN and overall performance monitoring, as well as their connection to various clinical disorders.

The current work also highlighted that disorders like anxiety, OCD, and narcissism often exhibit alterations in ERN amplitudes and error awareness (Banica et al., 2020; Moser et al., 2013; Gehring et al., 2000; Riesel, 2019; Xiao et al., 2011; Mück et al., 2023). This observation, in conjunction with the frequent display of dysfunctions in brain regions like the ACC and lPFC in these disorders, establishes a potential link between these conditions and error processing.

However, the study did not directly assess the impact of task parameters such as accuracy, speed, and motivational salience. Prior research has suggested that these elements can modulate ERN amplitudes (Gehring et al., 2018), leaving room for further exploration. Understanding how these factors interact with error awareness could provide even more comprehensive insight into these mechanisms. Therefore, while the study provides a significant contribution to the ongoing discussion on the role of conscious perception in error monitoring (Wessel, 2012), it also underscores areas for future investigation to enhance our understanding of these processes.

Limitations

Despite its valuable insights, the study presents certain limitations that may affect the validity of the conclusions, along with the generalizability and reliability of the findings. A key limitation is the binary measure for error awareness used, categorizing participants as either 'aware' or 'unaware.' This simplification might not fully capture the nuances and degrees of error awareness, potentially restricting the depth of understanding regarding its relationship with ERN amplitudes. Error awareness likely spans a spectrum, and alternatives like Likert scales could offer more comprehensive insights. Such scales would allow distinguishing between different levels of awareness and their distinct effects on ERN amplitudes. Unfortunately, the limited use of such measures in current research complicates their implementation in meta-analytic studies like this one.

This challenge extends beyond this study and is a prevalent issue in the field of cognitive neuroscience, underscoring the need for more sophisticated and sensitive measures of error awareness (Wessel, 2012).

Additional limitations include potential biases arising from the limited number of studies included in the meta-analysis, methodological diversity, and limited sample sizes in some of the included studies. The timeframe of the literature search, spanning articles published from 2010 to 2020, might have excluded more recent findings that could further elucidate the relationship between error awareness and ERN amplitudes.

Future Directions

Given the limitations identified, future research should focus on various unexplored aspects to enrich our understanding of error awareness. Further studies are recommended to investigate the roles of different brain regions in error processing, impacts of neurological and psychiatric conditions on ERN amplitudes, and potential benefits of conceptualizing error awareness as a spectrum. Larger and more diverse samples should also be considered to validate the current findings and provide a more robust understanding of error awareness and its neural correlates. An innovative line of exploration may lie in the adoption of continuous reporting techniques. These techniques offer an opportunity to move from the traditional binary distinction of 'aware' or 'unaware', towards a measure of error awareness that aligns with its conception as a spectrum. This method could offer a more refined and detailed understanding of the influence of different levels of awareness on ERN amplitudes.

Implicit measures of error awareness present another interesting avenue for future investigation. These measures, which assess error awareness based on behavior or physiological responses rather than conscious reports, might reveal facets of error processing and awareness that are not accessible through self-reports. For instance, a study by Wessel et al. (2011) utilized heart rate and pupil diameter as implicit measures, finding differential effects of error awareness on these physiological responses, thereby providing additional insights into unconscious error processing. This example underscores the potential of implicit measures to highlight the complexity of the neural machinery underpinning error detection and cognitive control, and their role in deepening our understanding of error awareness.

Incorporating machine learning techniques into the analysis of implicit measures and continuous reporting data offers another promising approach. Research has shown that machine learning, specifically deep learning with convolutional neural networks, can effectively decode task-related information from raw EEG data (Schirrmeister et al., 2017). Applying these techniques to data related to error awareness may facilitate more accurate and sensitive predictions. In the presence of potential discrepancies between machine learning predictions and self-reports, this approach could clarify aspects of error awareness that might not be consciously recognized, contributing to a more comprehensive understanding of error awareness.

As for population-specific research, examining error awareness and its influence on ERN amplitudes across diverse demographics, including children and the elderly, can augment our understanding of the developmental trajectory of error processing and its neural correlates across the lifespan. This could reveal potential age-related changes in error awareness, providing valuable insights into developmental and aging processes.

Lastly, given the methodological diversity in this field, adopting a multi-method approach could provide a more integrative view of error awareness. Such an approach could help capture the full spectrum of error awareness, thereby adding more depth and complexity to our comprehension of this critical neurocognitive event.

Societal and Ethical Considerations

Understanding the cognitive processes involved in error monitoring, specifically the role of error awareness, has potential implications across numerous fields. This knowledge could inform strategies to enhance performance in various domains. For instance, in educational or workplace settings, training programs could be designed to improve error awareness, thereby potentially improving learning and performance.

Moreover, insights from this study could be beneficial for clinical practice, guiding the development of interventions that enhance error detection and cognitive control, thereby improving safety and outcomes. However, potential psychological stress or self-criticism associated with increased error awareness should be considered when designing these interventions.

Nevertheless, as error awareness research often employs neuroimaging techniques, there are additional ethical considerations specific to this method of research. These include ensuring data privacy in handling neuroimaging data and the ethical issues surrounding the interpretation and potential misuse of such data.

Furthermore, the potential practical applications of these techniques beyond research, such as in performance-enhancing programs or clinical interventions, bring up even more ethical considerations. As the field potentially moves towards broader adoption of these applications, it becomes crucial to establish clear guidelines and safeguards for the use of these techniques to ensure the protection of individual privacy and ethical data use.

Conclusion

In conclusion, the present study substantially advances the understanding of the role of conscious perception in error monitoring by providing robust evidence for the relationship between error awareness and ERN amplitudes. The results emphasize the crucial role that conscious recognition of errors plays in the neural response of the ERN, thereby underscoring the importance of error awareness in performance monitoring and behavioral adaptation. These findings resonate with and enrich the theoretical understanding from the Error Detection Theory and the Reinforcement Learning Theory.

The study also uncovers potential links between error processing and various clinical disorders, offering valuable insights that could guide future clinical practices and research. Despite the important contributions of this study, it recognizes its limitations, such as the binary categorization of error awareness, the limited number of studies incorporated in the meta-analysis, and potential variations in methodology across these studies.

Given these limitations and the areas yet to be explored, future research is recommended to delve deeper into the complex relationship between ERN amplitudes and error awareness. This entails exploring the roles of various brain regions in error processing, evaluating the effects of neurological and psychiatric conditions on ERN amplitudes, and reconceptualizing error awareness from a binary state to a continuum.

Utilizing diverse methodologies, such as continuous reporting techniques, implicit measures of error awareness, and machine learning techniques, could yield a more nuanced understanding of these mechanisms. Investigating these aspects across different demographic groups and employing a multi-method approach could also provide a broader perspective on error processing and its evolution across different stages of life.

The potential applications of the findings from this study span across educational settings, workplaces, and clinical interventions. This underscores the urgency to establish ethical guidelines for research and practice in this domain. Safeguarding data privacy and maintaining ethical standards in the use of neuroimaging data are critical as research continues to delve into the intricate relationship between error awareness and ERN amplitudes.

In summary, this study serves as a significant advancement in the ongoing exploration of the role of conscious perception in error monitoring. It serves as a robust foundation for future investigations and highlights the potential practical applications of this knowledge across a range of fields.

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