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Review

Autistic traits and event-related potentials in the general population: A scoping review and meta-analysis

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ABSTRACT

Background: Differences in short and long-latency Event-Related Potentials (ERPs) can help us infer abnormalities in brain processing, considering early and later stages of stimuli processing across tasks and conditions. In autism research, the adult population remains largely understudied compared to samples at early stages of development. In this context, this scoping review briefly summarises what has been described in community and subclinical adult samples of autism.

Method: The current scoping review and meta-analysis includes 50 records (N = 1652) and comprehensively explores short and long-latency ERP amplitudes and their relationship with autistic traits in adult community samples.

Results: This meta-analysis identified, with small to medium effect sizes, distinctive patterns in late ERP amplitudes, indicating enhanced responses to visual stimuli and the opposite patterns to auditory tasks in the included sample. Additionally, a pattern of higher amplitudes was also found for the component P3b in autistic traits.

Discussion: Differential effects in visual and auditory domains are explored in light of the predictive processing framework for Autism. It remains possible that different brain mechanisms operate to explain symptoms related with different sensory modalities. P3b is discussed as a possible component of interest in future studies as it revealed a more robust effect for differentiating severity in the expression of autistic traits in adulthood.

1. Introduction

Autism Spectrum Disorders (ASD) cluster a wide variety of symptoms, from early abnormal sensations, such as hypersensitivity to sounds or visual fascination with lights or movement, to more complex impairments, including changes in social behaviour and communication (American Psychiatric Association, 2022; Lord et al., 2018). The greater recognition of ASD manifestations' complexity and severity led to changes in the Diagnostic and Statistical Manual of Mental Disorders (DSM) categories. The fifth edition now reframes the previous categories of diagnosis - Autistic Disorder, Asperger Syndrome, Childhood Disintegrative disorders, and Pervasive Developmental Disorder - under a single umbrella of the autism spectrum (American Psychiatric Association, 2022). This change led to a fundamental shift in the paradigm and ASD research. Disorders in the spectrum are no longer considered independent categories and a single expression of a clinical problem. Rather, there is a recognition of high phenotypic heterogeneity in ASD, which can be represented in a continuum of severity that extends into normative ranges (Ibrahim & Sukhodolsky, 2018). The Autism Quotient (AQ, Baron-Cohen et al., 2001) or the Social-Responsiveness Scale (Constantino & Todd, 2003) are some of the self-report scales that can be used to evaluate the expression of autistic traits from a dimensional point of view. Working from this framework may help to reach those individuals with high autistic trait scores but whose clinical

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manifestations do not reach the clinical diagnosis criteria of ASD (i.e., subclinical samples).

1.1. Autistic traits

Autistic traits are a set of personality characteristics that reflect the phenotypic expression of Autism in the general population. The presence of subclinical manifestations of ASD in the general adult population ranges from 5 % to 25 %, with the highest presence recorded in the young adult population (Dovgan & Villanti, 2021; Sasson et al., 2013). The prevalence of subclinical manifestation among children in the general population seems to be much lower, ranging from 1.4 % to 3.31 %, especially in female samples (Constantino & Todd, 2003; Kim et al., 2011; Morales Hidalgo et al., 2021). Interestingly, gender differences in autistic traits reported in children are not as evident in adults (Dovgan & Villanti, 2021; Rutherford et al., 2016; Ruzich et al., 2017; Sasson et al., 2013).

Several studies have found that individuals with high autistic traits in non-clinical populations reveal similarities to ASD patients, suggesting that Autism is best conceptualised as a continuous, dimensional construct that extends into the neurotypical population (Kozak & Cuthbert, 2016; Ruggero et al., 2019). In support of a dimensional hypothesis, individuals with high autistic traits have been shown to share similarities with ASD, including abnormalities in social behaviour (Constantino & Todd, 2003) or hypersensitivity to stimuli (Baron-Cohen et al., 2009). Further evidence for a dimensional hypothesis comes from neuroanatomy and brain function evidence in research with the non-clinic ASD population. Individuals exhibiting elevated autistic-like traits display a decrease in white matter volume in the posterior temporal sulcus (von dem Hagen et al., 2011). Moreover, diminished activation in this region is observed during face-to-face conversations (Suda et al., 2011),

Interestingly, the degree of atypical sensory experiences in the visual and auditory domains seems to explain improved performance in some tasks. A meta-analysis by Cribb and colleagues revealed that, similarly to clinical autism, individuals from the community who score highly on the AQ exhibit superior performance on visual tasks (Cribb et al., 2016). The same is found for the auditory domain, with improved perceptual processing being reported for auditory features (Stewart et al., 2018).

If individuals with high autistic-like traits in the general population share, although at a milder degree, similar neuronal and cognitive characteristics with individuals with Autism, then the study of community and subclinical samples may contribute to our understanding of ASD. Following the most recent approaches in the field arguing for a spectrum in neurodevelopmental and mental health problems (e.g., the new dimensional section in DSM-5, new dimensional models such as RDoC and HiTOP (American et al. (American Psychiatric Association, 2022; Kozak & Cuthbert, 2016; Ruggero et al., 2019), the study of these samples holds the promise to deepen our knowledge on how the strength of autistic traits may covary with brain alterations. For instance, research surrounding the severity of manifestations has been defined as an essential research priority in ASD (Lord & Bishop, 2015). Considering that atypical reactions to sensory stimuli are viewed as a core feature of Autism, it is important to examine how the brain processes this information. This can be explored through Event-Related Potentials (ERPs).

1.2. ERP components

Event-related potentials, an electroencephalography-based technique, have been widely used to explore the neural correlates of perception and cognition in non-autistic and autistic populations (Luck, 2014). ERP data provides high temporal resolution, allowing us to explore the time course of information processing in the brain with great detail. In this context, ERP can be used to analyse how incoming sensory information is processed at early (latency range 100–250 ms) or later (latency range >250 ms) stages of processing, before and after stimulus characteristics are fully encoded (Banaschewsk & Brandeis, 2007). Different ERP components included in the studies selected for this revision are described below.

1.2.1. Early ERP components (automatic stimulus processing and attentional orienting)

Early components represent the first stages of stimuli processing, which are often modulated by stimuli characteristics, attention, and an initial modulation of old versus novel stimuli, namely habituation or stimuli suppression (e.g., P50, P1, MMN, Hillyard et al., 1998; Näätänen et al., 2007; Smith et al., 1994). For a brief description of early ERP components addressed within the current analysis and their functional significance, see Table 1a.

In the visual modality, the earlier components included in this review are the P1 and N1 waveforms. The P1 peaks between 100 to 130 ms with larger amplitude over posterior sites. The P1 component is followed by the N1 wave, which can additionally be divided into at least two subcomponentes, namely the N1a subcomponent that peaks in anterior sites between 100–150 ms and N1b subcomponent that peaks 150–200 ms and arises from more posterior regions (Luck, 2014). Another N1 subcomponent within the 150–200 ms time window is the N170. The N170 is particularly sensitive to face or face-like stimuli (Luck, 2014; Rossion & Jacques, 2012). Following visual stimuli, in the anterior and central sites, the P2 waveform follows the N1 at around 200–250 ms. The P2 is larger for simple stimuli containing target features. In the auditory domain, a similar flow of waveforms can be described, namely the components P50, N1 or P2. There are, however, slight differences in components' latency and brain topography: P50 - peaks at around 40–80 post-stimulus; N1a - peaks between 70–150 ms and seems to be originated in the auditory cortex, showing frontocentral distribution; N1b – peaks between 100–300 ms in central brain regions, being more sensitive to attention and discriminative tasks (Banaschewsk & Brandeis, 2007; Luck, 2014).

Along the line of early sensory discrimination, the N2 is usually elicited by tasks with infrequent or deviant stimuli. This waveform is also called Mismatch Negativity (MMN) when computed by infrequent minus frequent stimuli. This waveform usually displays an anterior and central distribution for auditory stimuli and a more posterior distribution for visual tasks (Luck, 2014). Within the N2 family, other two subcomponents can be considered, namely the anterior N2b and the posterior N2c both within the 200–300 ms time window.

The N2b can be elicited by either auditory or visual stimuli and has an anterior distribution. This component is present when the deviant stimuli are attended to, and it is also related to response inhibition, such as the no-go response. An anterior similar waveform triggered to response feedback, which is frequently called feedback-related negativity (FRN), is expected to be larger for negative feedback (e.g., error) than for positive feedback (e.g., hits) (Hajcak et al., 2006; Luck, 2014). In a similar time window and location, the medial frontal negativity (MFN) is also measured after stimuli feedback, but it is computed as gains minus losses in Gambling tasks (Fukushima & Hiraki, 2009; Martin & Potts, 2011).

The N2c is a posterior negativity recorded for visually relevant targets. When the target is recorded in contralateral electrodes then the N2-posterior-contralateral (N2pc) occurs. By contrast, when the attentional priority for a salient stimulus is being suppressed, the distractor positivity (Pd) can be recorded. It has been proposed that the early directing attention negativity (EDAN), which occurs in the same time window and location as the N2pc, could represent the same waveform (Velzen & Eimer, 2003). However, this has recently been refuted, considering that EDAN might instead represent selective attention processes in the anticipation of an impending stimulus, namely in tasks that include an attention-directing cue prior to the target presentation (Praamstra & Kourtis, 2010). At occipital sites, an early posterior negativity (EPN) can further be observed following emotional content with larger amplitudes to pleasant and unpleasant stimuli compared to neutral (Kappenman &

Table 1a
Components classification per ERP group.

Early ERP Group				
Component	**Topography**	**Modality**	**Peak Latency**	**Functional Significance**
P50	Central	Auditory	40-50 ms	Sensory gating (Banaschewsk & Brandeis, 2007)
ERN (error related negativity)	Central	Visual	50-100 ms	Error detection following incorrect motor response (Luck, 2014)
P1	Posterior	Visual	100-130 ms	Low-level sensory processing, sensitive to variations in stimulus parameters (Luck, 2014)
N1a	Anterior/ Central Anterior	Auditory Visual	70-150 ms 100-150 ms	Sensory detection tasks (Luck, 2014)
N1b	Central Posterior	Auditory Visual	100-300 ms 150-200 ms	Sensitive to attention, discriminative processing (Luck, 2014)
N170	Posterior	Visual	140-200 ms	Face processing, expertise (Banaschewsk & Brandeis, 2007; Luck, 2014)
P2	Posterior and Central Anterior and Central	Visual Auditory (P160)	100-250 ms 100-300 ms	Larger for target stimuli, sensitive to habituation (Luck, 2014)
MMN (mismatch negativity)	Central Posterior	Auditory Visual	150-250 ms	Relatively automatic response to a stimulus that differs from the preceding stimuli; Pre-attentive change detection (Banaschewsk & Brandeis, 2007; Luck, 2014)
EPN (early posterior negativity)	Posterior	Visual	150-300 ms	Early stimuli processing; affective valence of stimuli (Kappenman & Luck, 2011)
N2b	Anterior	Auditory Visual	180-325 ms	Deviation in form or context of a prevailing stimulus, sensitive to attention, response inhibition (Luck, 2014)
N2c N2pc (posterior-contralateral)	Posterior	Visual	200-300 ms	Task relevant targets, contralateral to an attended object (N2pc), detection of target probability (Luck, 2014)
Pd (distractor positivity)	Posterior	Visual	200-300 ms	Object that is being suppressed (Luck, 2014)
EDAN (early directing attention negativity)	Posterior	Visual	200-300 ms	Attention orienting to the cued location
MFN (medial-frontal negativity)	Anterior	Visual	200-300 ms	Performance monitoring (Kappenman & Luck, 2011)
FRN (feedback-related negativity)	Anterior and Central	Visual	200-300 ms	Feedback processing, reinforcement learning (Hajcak et al., 2006; Luck, 2014)

Luck, 2011).

Finally, Error-related negativity (ERN) or Ne is a very early negativity (50–200 ms after response) that is assumed to represent the detection of errors in performance (Falkenstein et al., 2000).

Overall, early stages of stimuli processing are particularly interesting for autism research, considering symptoms such as hypersensitivity, context updating, or even emotion recognition (e.g., N170, Kang et al., 2018). In ASD samples, amplitudes were reduced for auditory components N1 and N2, and visual N170, although the number of studies with adult samples was very limited (Kang et al., 2018; Williams et al., 2021). MMN was shown to be reduced for children with Autism, but this was not significant for adults who showed equal or larger amplitude responses (Chen et al., 2020; Schwartz et al., 2018). A similar meta-analysis included electrophysiological studies on performance monitoring, namely ERN and FRN, but the number of studies was very scarce (Hüpen et al., 2016).

1.2.2. Late ERP components (later attentional and executive functions)

Later ERP components have been linked to later stages of processing, including more complex cognitive features such as working memory, or language processing (e.g., P300, N400, (McCarthy et al., 1995; Polich, 2000), which also have been described to be affected in ASD (Ibrahim & Sukhodolsky, 2018). For a brief description of late ERP components addressed within the current analysis and their functional significance, see Table 1b.

The most studied ERP is the P3 or P300. However, there are several distinguishable components within the range of the P3 wave (300–500 ms) which have been supposed to underlie different cognitive mechanisms. The classic P3 or P3b shows a parietal scalp distribution and is thought to represent the first categorization of the stimulus as rare or frequent in both auditory and visual paradigms (Luck, 2014). In the same time window, the feedback P3 (Fb-P3) is elicited by motivational salience of feedback instead of performance feedback (e.g., the monetary incentive delay task (Gao et al., 2023).

Some components inherently related to P3 modulation (Fields, 2023) have been linked to affective processing (Dien et al., 2004). The Late Positive Potential (LPP) occurs between 300–700 ms in centroparietal regions and is related to increased attention to stimuli with affective content (vs. neutral) (Kappenman & Luck, 2011). In the auditory modality, a similar but negative waveform appears as a response to emotional audio recordings, the late negative component (LNC, Friedman & Johnson, 2000). Later in the processing stream, about 500 ms, a broad positive potential peak over parietal brain areas in response to emotionally arousing pictures. The Late Positive Complex (LPC) has generally been associated with task demands such as attentional capture, evaluation, or memory encoding (Friedman & Johnson, 2000; Kissler et al., 2009).

Late ERPs are also used to study anticipation and attention. The Contingent Negative Variation (CNV) is a broad negative deflection between a warning and a target stimulus that reflects the anticipation of an action (Kappenman & Luck, 2011). A subcomponent of the CNV is the

Table 1b
Components classification per ERP group.

Late ERP Group Component	Topography	Modality	Latency	Functional Significance
fb-P3 (feedback P3)	Anterior or Central	Visual or Auditory	300-450 ms after feedback onset	Performance feedback or outcome evaluation (Gao et al., 2023)
P3b	Posterior	Visual or Auditory	300-650 ms	Task-relevant unpredictable, infrequent changes in the stimuli, memory tasks, decision-making (Luck, 2014)
ADAN (anterior directing attention negativity)	Anterior	Visual	300-500 ms	Attention holding at the cued location (Praamstra & Kourtis, 2010)
N400	Central and posterior	Visual or Auditory	300-500 ms	Violations of semantic expectancies (Luck, 2014)
SN (sustained negativity)	Posterior	Visual or Auditory	300-700 ms	Attention, Cognitive processing (Kappenman & Luck, 2011)
LNC (late negative complex)	Anterior	Auditory	450-650 ms	Evaluation of emotional information (Friedman & Johnson, 2000)
LPC (late positive complex)	Posterior	Visual	400-800 ms	Evaluation of emotional information, Explicit recognition memory, (Friedman & Johnson, 2000; Kissler et al., 2009)
LPP (Late Positive Potential)	Central	Visual	400-600 ms	Evaluation of emotional information (Kappenman & Luck, 2011)
P600	Posterior	Visual or Auditory	500-700 ms	Syntactic violations (Luck, 2014)
ULP (Ultra-Late Potential)	Anterior	Somatosensory	950–1200 ms	Response to stimulation of C-nociceptive fibers (Haggarty et al., 2020)
CNV (Contingent Negative Variation)	Posterior	Visual	1000–1500 ms after cue onset	Stimulus triggering a prompt action (Kappenman & Luck, 2011)
SPN (Stimulus-Preceding Negativity)	Posterior	Visual or Auditory	1000–1500 ms after cue onset	Anticipating stimuli carrying important information (Kappenman & Luck, 2011)

stimulus-preceding negativity (SPN), which is negativity that grows as the individual anticipates the occurrence of an information-bearing stimulus, irrespective of whether an overt response is required for this stimulus (Luck, 2014). Both of these potentials slowly increase their negative shifts that continue to increase up to a significant event. Both the CNV and SPN have been found to be larger when participants believe that an upcoming stimulus is either pleasant or unpleasant (vs. neutral) (Gladhill et al., 2022; Poli et al., 2007).

Language processing mechanisms can further be evaluated via late components. N400 is a negative-going wave that is usually largest over central and parietal sites and typically seen in response to violations of semantic expectancies (Luck, 2014), while syntactic violations elicit the P600 with a latency of 500–800 ms (Osterhout & Holcomb, 1992).

Overall, long-latency ERPs offer a window into the dynamic interplay of neural networks during tasks that demand sustained cognitive engagement. Few meta-analyses have explored the link between late brain components and ASD. The components P3a and P3b were found to be reduced in ASD samples under 18, but more studies are needed to reach robust conclusions about the adult population (Cui et al., 2017). This evidence provides an initial insight towards understanding the developmental trajectory of long-latency ERPs in ASD, highlighting the need for further research to elucidate how these components evolve across the lifespan and contribute to the cognitive profile of individuals with autism.

1.3. Purposes of this review

Overall, the few meta-analytical reports on ERPs and ASD do not include subclinical levels of ASD, which could help to substantially increase the evidence. To ensure that ERP components are not influenced by brain maturity or other developmental factors (Beauchamp et al., 2011; van Dinteren et al., 2014), this review will focus on adult samples, which are underrepresented in the available meta-analyses (Chen et al., 2020; Cui et al., 2017; Williams et al., 2021). Most ERPs are expected to stabilize around 18 years old, with evidence showing that ERPs reach maturity at late adolescence (Beauchamp et al., 2011; Dinteren et al., 2014). Also, most autism research focuses on children, and studying Autism in adulthood is an essential addition to investigating the condition's effects across the lifespan.

To our best knowledge, no meta-analysis or systematic review has provided a comprehensive understanding of how a wide array of ERP components are characterized by autistic traits in their amplitude modulation. In this sense, this scoping review aims to fill the gaps in the literature and contribute to a deeper characterization of how early and late ERP components relate to autistic traits in adulthood in both visual and auditory domains.

2. Method

2.1. Registration

The study protocol was publicly registered in the Open Science Framework (OSF) during the data extraction and before any data analysis. The protocol was only registered after the formal screening of search results against the eligibility criteria because we were unsure of having enough available data to perform a meta-analysis on ERP amplitudes. After scanning the available preliminary data, we decided to proceed with the meta-analytical plan described in the registered protocol available at https://osf.io/z2n86.

2.2. Search strategy

Records were identified by systematically searching several electronic databases: PubMed (Medline), Web of Science Core Collection, and EBSCO (Psychology and Behavioral Sciences Collection, APA PsycArticles, APA PsyInfo, and Open Dissertations). The terms "Autism" and "Event-related Potentials" were used for the search query, including variants and MeSH for these terms (full search query available in the supplemental material). A first search was conducted on November 23rd, 2021, and was subsequently updated on October 12th, 2022. Additional records were also retrieved by scanning the reference lists of literature reviews addressing ASD and ERP. Full search terms can be found in the supplementary material.

2.3. Eligibility criteria

Records were included if they met the following criteria: (1) Empirical studies with quantitative data written in English, (2) community sample assessed with at least one measure of autistic traits, (3) at least one measure with ERP technique acquired with EEG, at any time window elicited by a stimulus or an event.

Regarding the first criterion, cross-sectional, longitudinal, and

experimental studies were included. Theoretical research papers, commentaries, case reports, editorial and qualitative studies were excluded.

For the second criterion, records were included if they reported non-clinical samples with at least one measure of autistic traits in between-group differences and/or correlational design. Group analysis covered records that reported high and low autistic trait groups. Records with clinical samples were included if they reported a control group assessed with at least one measure of autistic traits. Only the control group sample was included in the review in these cases. Other personality traits (e.g., impulsivity, antisocial) were not excluded as long as these scores did not meet the cut-off for clinical diagnosis.

2.4. Study selection and data coding

The total records were loaded first to Zotero (Rosenzweig, 2016) and then to Rayyan (Ouzzani et al., 2016) to check and remove duplicates. One researcher (PM) screened the non-duplicate records by title and abstract to remove studies that were clearly out of topic. The remaining records were then fully text-screened by three blinded researchers (HG, IM, and PM) to determine their eligibility for the review: PM examined 100 % of the records, and HG and IM examined 50 % each. As such, two researchers examined each record independently (PM and either HG or IM). Conflicts between researchers were solved by one researcher (RP) in a meeting with the research team. The number of records at each step, including the number and reasons for exclusions, are reported in the results section.

For data extraction, a spreadsheet was developed to extract the required information from the included studies, namely: (1) Study information - title, authors, and publication year; (2) Variables related to the sample - sample size, the percentage of females, mean age, Autism measure, and Autism total score mean; (3) ERP component amplitude means and standard deviations or t-test and p-value between groups or correlation values; (4) ERP characteristics - nomenclature, time window, electrode or electrode cluster, hemisphere, region (anterior, central or posterior), and type of amplitude measurement (e.g., baseline to peak); (5) Conditions related to ERP task - task name, task type (active or passive), stimuli type (visual, auditory, or somatosensory), stimuli complexity (simple - e.g., pure tones, shapes, or complex - e.g., faces, words), the process involved (affective - e.g., emotion recognition task or cognitive - e.g., sensory gating), and stimuli condition (control - e.g., g., neutral, standard stimuli, or target - e.g., rare, deviant, non-neutral). For the ERP task-related conditions, we considered a task active if the participant had to provide a response during the task, such as pressing a button. Also, tasks that included emotional content or social interaction were classified as affective, while tasks that did not include these stimuli, such as simple visual search or sensory gating tasks, were labelled cognitive. This distinction is relevant as abnormalities in social-emotional reciprocity and affect are considered a core deficit of autistic traits (American Psychiatric Association, 2022; Jeste & Nelson, 2009). In this sense, we aimed to understand if tasks that included these domains could explain differences in ERP amplitudes in autistic traits. Finally, rare, deviant, or non-neutral stimuli were allocated as targets, and neutral or standard stimuli were classified as control. Albeit, this was adapted for each task, as described by the respective authors.

The records were further separated by age groups, and data extraction was only conducted for the adult population. Reports of children including autistic traits and ERP measures of their parents were also included in this study, considering only the parents' sample.

For effect size calculation in between-group analyses, means and standard deviation for each group were coded whenever possible. Alternatively, Cohen's *d*, *t*, *F*, and *p*-values were considered if these statistics permitted estimating the effect size of interest. For correlational analyses, only zero-order Pearson correlations were retrieved.

Effect sizes were computed so that a positive effect represents reduced amplitude in the high autism groups (group-based analyses) or amplitude reduction with higher self-report scores in autism trait questionnaires (correlational analyses).

Missing information for effect size calculation and other queries regarding included studies (e.g., unclear information, missing demographic information) were requested by email to the authors. Studies were excluded if no information was available for effect size calculation and the authors did not reply to the request. A total of 63 authors were contacted for missing information for one or more records. On four occasions, the corresponding author's email was not available anymore, and more recent contacts for these authors were not found. We recorded a response rate of 31 % for the remaining 59 authors who received the email. Any inconsistencies after verification were clarified with the original authors or addressed in a meeting by the research team.

2.5. Analytical strategy and meta-analytic methods

The effect sizes were estimated as Hedges' *g* (Hedges, 1981), as this metric provides a correction factor that reduces the effect size overestimation bias (which may be especially problematic in studies with small samples). It is important to notice that the same record could originate group-based and correlational effect sizes (e.g., a study could be included for group comparison of high vs low autistic traits using extreme quartiles as well as continuous correlations between autistic scores and mean amplitudes), which were then combined for the overall and moderation analysis. The software computed a composite score for each study using the mean of outcome/ data entry to combine different data entries for each study (distinct outcomes or correlational and group-based data in the same study).

For the meta-analytical review, we included early and late ERP amplitudes with no restrictions regarding topography or nomenclature. Following the suggestion of Banaschewsk and Brandeis (2007) and Luck (2014), an early ERP was defined as a 50–250 ms latency component, representing the initial stages of stimulus processing, while later stages included later (>250 ms) components. A summary of all retrieved components and how they were classified can be found in Table 1. For group analysis, only the absolute values for means and standard deviation were retrieved such that negative components resulted in positive values if reported negative. In occasions where positive and negative amplitudes were reported for the same component (e.g., the effective area under the curve, mean values), the amplitude sign was maintained for positive and inverted for negative components. For correlation analyses, negative effects for negative components were multiplied by −1 unless the report explicitly mentioned that this was performed for the available data.

Random effect models were used for each meta-analysis. For meta-analyses with multiple effect sizes stemming from the same sample, a mean effect size was calculated to account for the lack of independence between effects. Data analysis was conducted using the Comprehensive Meta-Analysis software (version 3.0; Biostat, USA, Borenstein et al., 2022).

Heterogeneity of effect sizes and publication bias were also evaluated on overall effect sizes for each analysis. The variability between studies, i.e., the differences in effect sizes that are caused by factors other than chance (sampling error), were tested on overall effect sizes using the *Q* statistic (Cochran, 1954) and described via the I^2 statistic (Higgins et al., 2011). Subgroup analyses were used for categorical moderators, namely: (a) stimuli modality (visual, auditory, or somatosensory), (b) stimuli complexity (simple - e.g., pure tones, shapes - versus complex - e.g., faces, words), (c) passive versus active type, (d) cognitive (e.g., sensory gating) versus affective tasks (e.g., emotional faces), (e) ERP nomenclature, (f) Amplitude measure (mean or area versus peak), (g) target (rare, deviant, non-neutral) versus control stimuli (neutral, standard stimuli). Meta-regressions were conducted for the continuous variables such as the percentage of females, age, and autistic measure score of the correlational studies - that included mean scores for the whole sample. For the autistic measure score, the meta-regression included only the total score for the Autism Quotient as insufficient

studies included other measures to run this analysis. Publication bias was assessed using Eggers's test of intercept bias (Egger et al., 1997). Hedges' *g* values, 95 % confidence intervals, and *p*-values were reported for each analysis.

3. Results

3.1. Search results

A detailed flow diagram of study selection was developed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Fig. 1, Page et al., 2021, Tricco et al., 2018). A total of 1810 records were retrieved after the electronic search, and 741 were identified as duplicates and removed. A total of 1069 were screened by title and abstract, and 197 were removed as out of topic. The remaining records were full-text screened for eligibility (n = 872). From these, 175 met the eligibility criteria, and 84 were included in the adult subgroup for this analysis. In the adult subgroup, 43 records did not report enough information to compute effect sizes, and the authors did not reply to the information request. A manual search of the reference list of included studies also added 14 records. Thus, a total of 48 records were included. Two studies reported the same dataset and two separate studies included two different samples in the same report. The total number of included datasets was updated to 50, encompassing 1652 participants. We used Cohen's kappa to compare the agreement between the researchers regarding the decision to include or exclude the eligible studies, revealing an almost perfect agreement (K =.84).

3.2. Study characteristics

The main characteristics of each report included in the scoping review and meta-analysis can be found in Table 2. A total of 67 % of the studies were published in the last five years. Most studies reported correlations (31), nine included only group means, and eight reported or sent information on both group and correlation analysis. The most studied ERP was P1, which was included in 12 of the 50 studies. The self-reported measure most frequently used to assess autism traits was the total score of the Autism Quotient scale (85 % of studies).

3.3. Meta-analysis on early ERP components

For early components, the quantitative analysis comprised 37 samples. The most frequently studied component was P1 (12 samples), followed by N1 (9 samples) and N2 (8 samples), N170 (6 samples), P2 (6 samples), MMN (5 samples) and FRN (4 samples).

Overall, we found no statistical association between autistic traits and early ERP amplitudes, neither in visual ($g = 0.03$, 95 % CI [−0.16, 0.22], $p = .760$) nor auditory domains ($g = 0.38$, 95 % CI [−0.30, 1.07], $p = .273$). The heterogeneity test identified a large variance across studies ($Q_{33} = 134.73$, $p < .001$, $I^2 = 75.51$ %). There was no evidence of publication bias in this analysis ($b = 1.07$, $p = .410$, table S1).

Moderation analysis by ERP revealed no statistically significant results ($p > .118$, tables S2, S3, and S4). Forest plots for P1, N1, N170, N2, and P2 can be found in Fig. 2. Meta-regressions revealed that studies with higher percentages of females and age mean revealed larger negative effects (table S2). No other moderation analysis was statistically significant (all *ps* > .139, tables S3, S4).

3.4. Meta-analysis on late components

We included a total of 38 samples, and the most frequently studied component was P3b (11 samples), followed by N400 (9 samples), Fb-P3 (7 samples), LPC (5 samples), LNC (3 samples), LPP (3 samples) and CNV (2 samples).

The analysis by stimuli revealed reduced late components amplitudes for auditory stimuli with higher traits of Autism (g = 0.42, 95 % CI

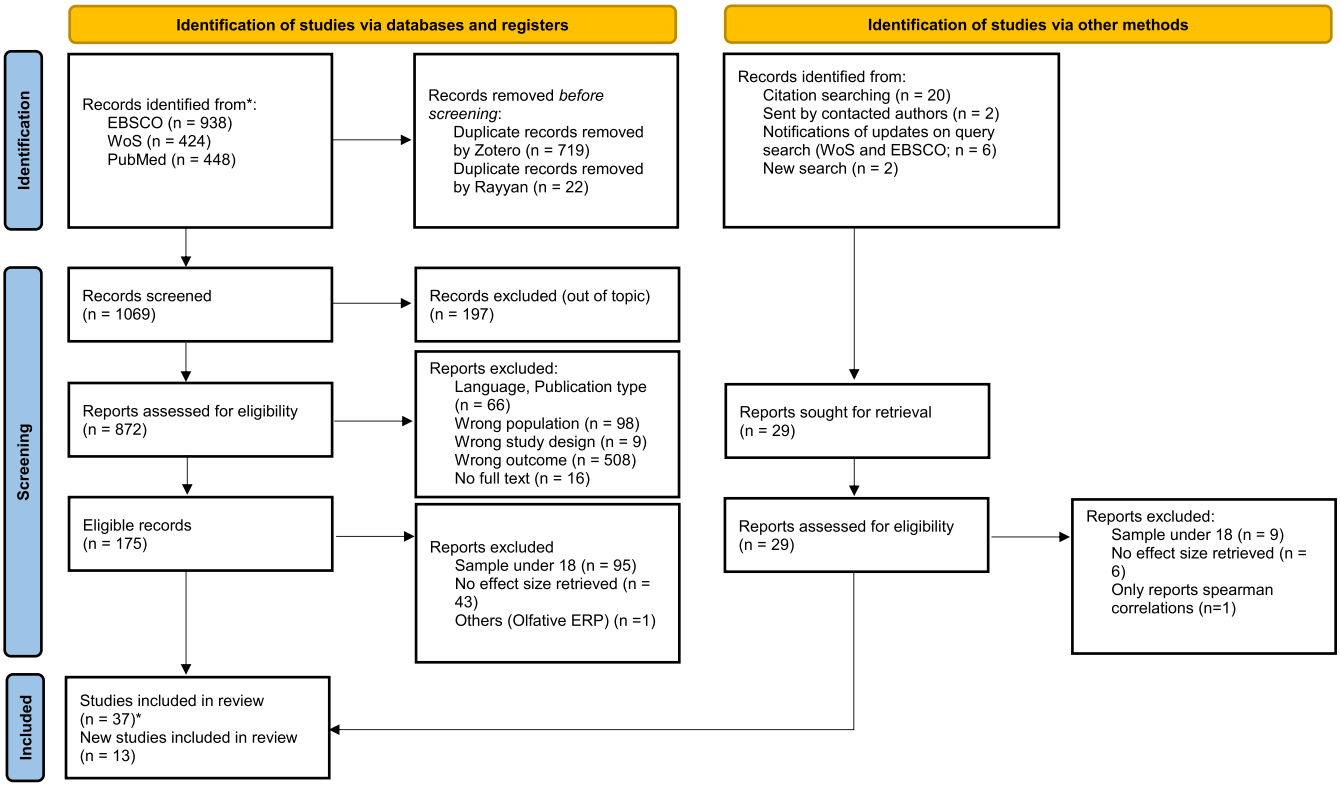


Fig. 1. PRISMA 2020 flow diagram for new systematic reviews with included searches of databases, registers, and other sources. *Two studies reported the same dataset and two studies reported 2 different samples.

Table 2
Characteristics of the included studies. N/A – not available, ERP – Event-related Potential, AQ – Autism Quotient, SRS - Social-Responsiveness Scale, BAPQ -Broad Autism Phenotype Questionnaire.

Meta-analytic design		Study	Autism Measure	n	Females (%)	Mean sample age	Mean autism score	Task Description	Stimuli	Process	Task Type	ERP	Time window (ms)	Region	ERP measure
Correlation	Group														
x	-	Aykan et al., 2020	AQ	66	49	23.0	17.4	Sensory Sensitivity Scales	Auditory Visual	Cognitive	Passive	N1a P2 N2c P2	75-117 135-192 124-192 213-264	Central Central Parietal Central	Peak
x	x	Barzy et al., 2020	AQ	22	21	32.6	18.1	Speaker-consistent and inconsistent semantic and pragmatic cues	Auditory	Cognitive	Active	N400	300-500	Anterior	Mean
-	x	Burt et al., 2017	AQ	33	57	24.7	18.3	Emotional Face recognition	Visual	Affective	Active	P1 N170	90-150 200-400	Posterior	Mean
x	-	Canal et al., 2019	AQ	50	60	23.7	18.9	Humorous and non-humorous passages	Visual	Cognitive	Active	N400 P600 LPC	300-500 500-700 700-1100	Anterior Posterior Posterior	Mean
x	x	Chen et al., 2021	AQ	22	50	18.6	28.3	Revised Iowa gambling task	Visual	Cognitive	Active	FRN	200-400	Central	Mean
x	x	Cox et al., 2015	SRS-A	35	54	24.1	45.4	Cued-incentive delay task	Visual	Cognitive	Active	Fb-P3	200-400	Posterior	Peak
x	-	Crasta, 2016	SRS-A	24	50	23.7	37.9	Sensory gating paradigm	Auditory	Cognitive	Active	N1a P50	70-180 40-50	Central	Peak
-	x	De Pascalis et al., 2020	AQ	50	100	23.0	14.9	Emotional Face recognition	Visual	Affective	Active	P3b	200-390	Posterior	Peak
x	-	Desai et al., 2019	AQ	27	67	22.9	14.9	Emotional Face recognition	Visual	Affective	Active	N170	132-204	Posterior	Peak
x	-	Dunn et al., 2016 -Study 1	AQ	22	50	23.4	18.7	Spatial attention task	Visual	Cognitive	Active	P1	70-170	Posterior	Peak
x	-	Dunn et al., 2016 - Study 2	AQ	36	72	20.5	18.7	Spatial attention task	Visual	Cognitive	Active	P1 N2pc Pd	70-170 180-300 230-280	Posterior	Peak Mean Mean
-	x	Fan and Cheng, 2014	AQ	20	5	22.0	21.0	Task-irrelevant emotional syllables or nonvocal oddball	Auditory	Affective	Passive	MMN	150-250	Anterior	Mean
x	x	Ferguson et al., 2021	AQ	24	33	34.0	18.8	Reading anomaly detection task	Visual	Cognitive	Active	N400	300-500	All	Mean
x	-	Fukushima and Hiraki, 2009	AQ	45	44	19.5	24.1	Gambling task	Visual	Cognitive	Active	Fb-P3 MFN	200-600 200-300	Central Anterior	Peak Mean
x	-	Gayle et al., 2012	AQ	45	36	19.8	14.5	Emotional faces oddball	Visual	Affective	Active	MMN	150-425	Posterior	Mean
x	-	Goris et al., 2018	AQ SRA-A	24	33	31.7	16.1 35.7	Hierarchical auditory oddball task	Auditory	Cognitive	Passive	MMN P3b	80-220 400-650	Anterior Posterior	Mean
x	-	Grisoni et al., 2019	AQ	22	64	26.2	17.3	Distraction-oddball paradigm with human action, or biological sounds and words	Auditoryand Visual	Cognitive	Passive	MMN	550-570	Anterior	Mean
x	x	Haase et al., 2019	AQ	29	62	26.2	17.3	Probe word task	Visual	Cognitive	Active	N400	400-500	Posterior	Mean
x	x	Haggarty et al., 2020	AQ	17	82	23.7	17.3	Fast and slow stroking touch discrimination	Somatosensory	Cognitive	Active	P3b ULP	250-500 3000-3400	Central Posterior	Peak
-	x	Ishikawa et al., 2017	AQ	19	46	19.9	21.9	Short stories in which the final sentence included either an expected or an unexpected word	Visual	Cognitive	Passive	P1 N2b P3b	50-150 150-250 250-350	Posterior Anterior Posterior	Mean
x	-	Iwanami et al., 2014	AQ	18	33	31.1	14.0	Novelty oddball task	Visual	Cognitive	Active	P3b	250-500	Posterior	Mean

(*continued on next page*)

Table 2 (*continued*)

Meta-analytic design		Study	Autism Measure	n	Females (%)	Mean sample age	Mean autism score	Task Description	Stimuli	Process	Task Type	ERP	Time window (ms)	Region	ERP measure
Correlation	Group														
x	-	Kaplan-Kahn et al., 2021	AQ Attention to detail	56	55	19.5	4.4	Pictures of animals presented simultaneously with an animal sound	Auditory and Visual	Cognitive	Active	P1 N400	50-150 300-500	Posterior Anterior	Mean
x	-	Kasai and Murohashi, 2013	AQ	16	56	25	20.6	Sustained focal-attention task with bilateral stimulus arrays	Visual	Cognitive	Active	P1 N1b N1b	100-140 140-180 180-220	Posterior	Mean
x	-	Kiyama et al., 2018 – Exp. 1	AQ	21	43	20.0	20.3	Sentence-final particles judgement task	Auditory	Cognitive	Active	EPN	150-400	Posterior	Mean
x	-	Kiyama et al., 2018 – Exp. 2	AQ	22	64	21.2	22.5	Content comprehension task	Auditory	Cognitive	Active	EPN	150-400	Posterior	Mean
x	-	Kulakova and Nieuwland, 2016	AQ comunication	23	63	22.0	2.4	Silent reading of sentences with antecedent-final and sentence final words	Visual	Cognitive	Passive	N400	350-500	Anterior	Mean
x	x	Lassale et al., 2015	AQ	68	31	20.9	21.3	Gaze-Cueing paradigm	Visual	Affective	Active	P1 EDAN ADAN	70-130 200-300 300-500	Posterior Posterior Anterior	Peak Mean Mean
-	x	Carter Leno et al., 2016	SRS-A	31	65	23.5	41.3	Behavioral task and feedback on task performance	Visual	Cognitive	Active	FRN	200-350	Anterior	Mean
-	x	Li et al., 2020	AQ	52	50	20.0	21.4	Pain and Attractiveness judgment task – Painful and non-painful faces	Visual	Affective	Active	N1a N170 N2b P2 P3b LPC	115-130 160-180 225-245 165-185 295-315 400-800	Anterior Posterior Anterior Posterior Posterior Posterior	Mean
x	-	Lui et al., 2018	AQ	30	0	21.6	21.1	Semantic valence judgment of positive and negative words spoken in either happy or sad tones	Auditory	Affective	Active	N2b N400	50-200 350-600	Central	Mean
x	-	Matyjek et al., 2020	AQ	51	51	27.8	18.3	Cued incentive delay task	Visual	Cognitive	Active	CNV Fb-P3	1000-1500 300-500	Central	Mean
x	x	Matyjek et al., 2022 - preprint	AQ	53	57	31.3	18.6	Cued incentive delay task	Visual	Cognitive	Active	N1a P1 N2c Fb-P3 SPN CNV	– – – 230-500 1000-1500 1000-1500	Anterior Posterior Posterior Posterior Posterior Posterior	Mean
-	x	Meng et al., 2020	AQ	40	50	19.3	21.3	Passive listening of neutral and painful voices	Auditory	Affective	Passive	N1a P2 LNC	100-300 100-300 400-700	Anterior Central Anterior	Mean
-	x	Meng et al., 2021	AQ	60	50	21.1	20.9	Emotional Face recognition	Visual	Affective	Active	P1 N170 P2 P3b LPC	130-140 160-180 100-300 300-340 400-600	Posterior Posterior Posterior Central Central	Mean
x	-	Milne et al., 2013	AQ	36	–	20.1	17.7	Visual search task and feature-based selective attention task	Visual	Cognitive	Active	P1 P3b	70-150 350-600	Posterior	Peak Mean

(*continued on next page*)

Table 2 (*continued*)

Meta-analytic design		Study	Autism Measure	n	Females (%)	Mean sample age	Mean autism score	Task Description	Stimuli	Process	Task Type	ERP	Time window (ms)	Region	ERP measure
Correlation	Group														
x	-	Naples et al., 2017	BAPQ Social BAPQ Rigidity AQ	15	22	21.5	37.3 23.7 10.9	Gaze sensitivity with simulated face-to-face interaction with onscreen faces	Visual	Cognitive	Active	N170 Fb-P3	130-225 350-450	Posterior	Peak Mean
x	-	Nieuwland et al., 2010	AQ	29	45	20.2	–	Reading of underinformative and informative sentences	Visual	Cognitive	Passive	N400	350-450	Posterior	Mean
x	-	Nijhof et al., 2018	AQ	24	33	31.4	15.3	Task-irrelevant deviant oddball with own name, close other and unknown other	Auditory	Cognitive	Active	N1b P3a P3b	130-210 290-350 380-440	Central Anterior Posterior	Mean
x	-	Nijhof et al., 2021	AQ	20	41	30.9	14.4	Attentional Blink task with own name, close other and unknown other	Visual	Cognitive	Active	N2c P3b	250-310 320-380	Posterior	Mean
x	-	O'Rourke and Coderre, 2021	AQ	20	–	25.2	15.5	Implicit semantic priming task	Visual	Cognitive	Active	N400 LPC	300-500 600-800	Central	Mean
x	x	Peled-Avron and Shamay-Tsoory, 2017	AQ	53	62	23.0	15.9	Passive viewing of social interaction (touch, non-touch) and object images	Visual	Affective	Passive	P1 LPP	50-150 400-600	Posterior	Peak Mean
x	-	Rolison et al., 2018	AQ BAPQ	16	63	20.7	33.6	Competitive treasure-hunt game against a computer and against a human partner	Visual	Cognitive	Active	P1 N2c FRN Fb-P3	100-200 100-250 250-265 310-465	Posterior Posterior Anterior Central	Peak Peak Mean Peak
x	-	Santesso et al., 2011	AQ	16	25	35.7	–	Flanker task	Visual	Cognitive	Active	ERN	50-100	Anterior	Peak
x	-	Sherman, 2016	AQ	103	53	–	18.8	Non-Social Arousal Task, Facial Emotion Task, Facial Processing task	Visual	Affective	Passive	N170 LPP	130-220 400-1000	Central Posterior	Mean
x	x	Takahashi et al., 2014, 2019	AQ	22	68	21.9	24.1	Same-Different task	Visual	Cognitive	Active	P3b PSW	300-500 500-800	Central	Mean
x	-	Wang et al., 2021	AQ	33	61	20.9	–	False-belief task	Visual	Cognitive	Active	LNC LPC	380-500 320-440	Anterior Posterior	Mean
x	-	Wei et al., 2019	AQ	26	23	19.3	–	Spatial cueing task	Visual	Cognitive	Active	P2	150-160	Posterior	Mean
x	x	Yang et al., 2022 – Exp. 1	AQ	30	50	21.0	26.5	Passive viewing of social-emotional and non-social emotional pictures	Visual	Affective	Passive	N1a N2b P2 P3b LPP	80-120 210-250 200-240 310-350 400-700	Anterior Anterior Posterior Posterior Posterior	Mean
x	x	Yang et al., 2022 – Exp. 2	AQ	33	49	21.4	29.7	Passive listening of social-emotional and non-social emotional audio recordings	Auditory	Affective	Passive	N1a LNC	100-300 300-700	Anterior Anterior	Mean
x	-	Zhao et al., 2015	AQ	45	44	–	–	Oddball paradigm with informative and uninformative sentences	Auditory	Cognitive	Passive	MMN SN	160-240 300-600	Anterior Posterior	Mean

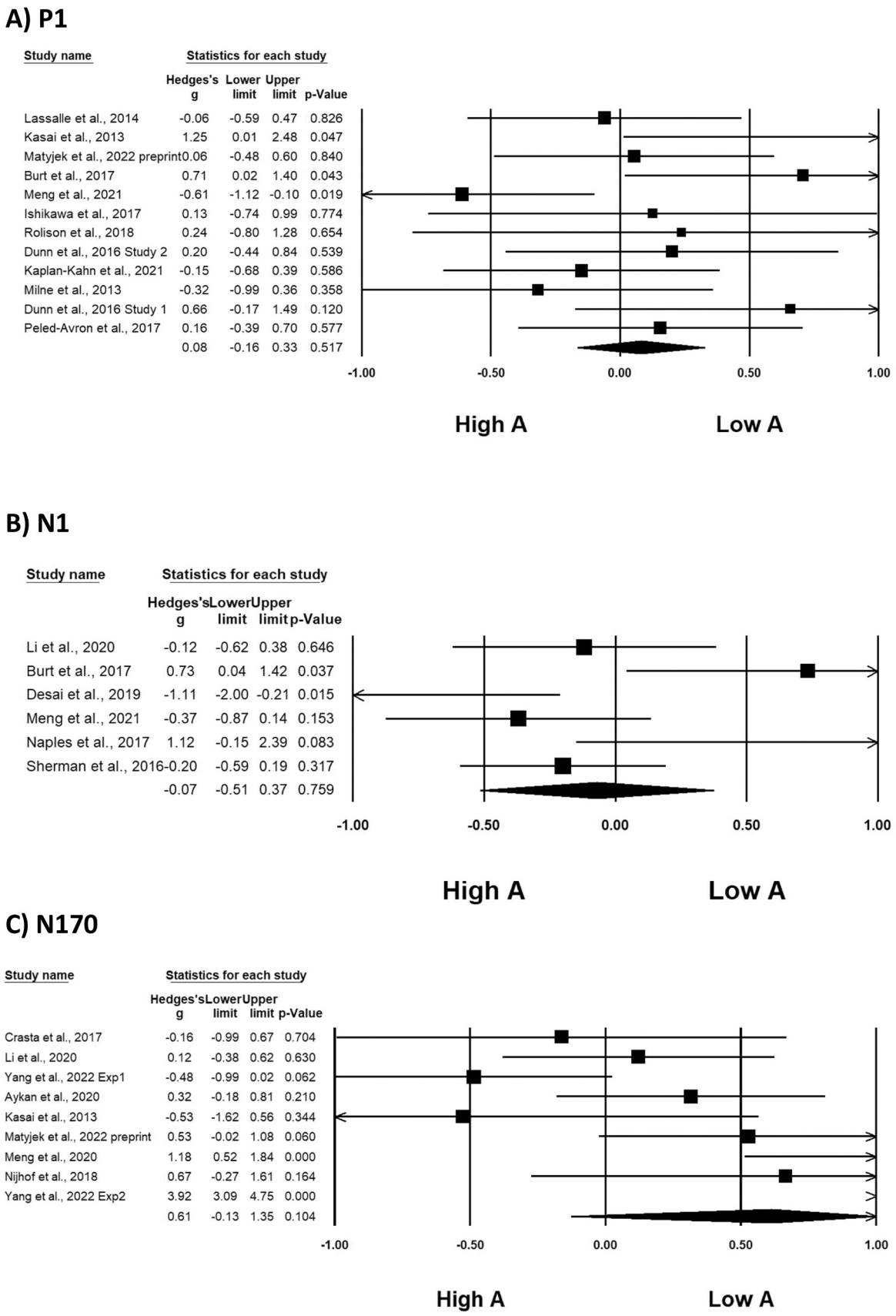
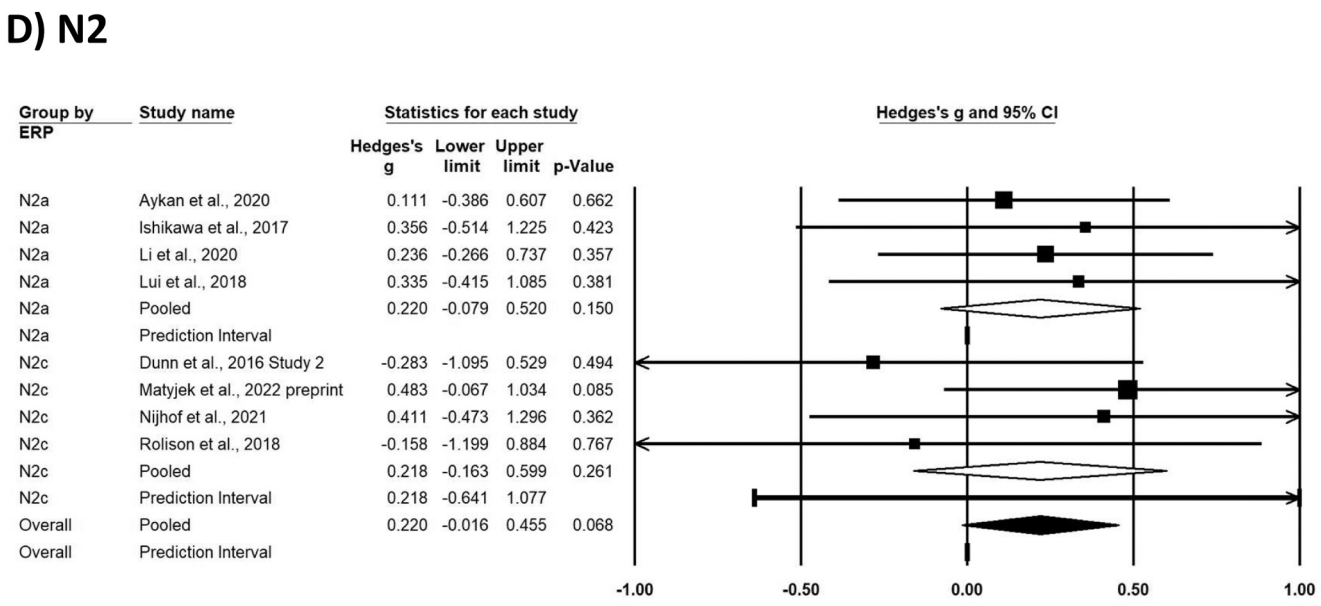


Fig. 2. Forest plots for meta-analysis of ERP amplitude grouped by ERP component. Each study is identified by study name and Hedges' g values, 95 % confidence intervals, and p-values are reported, as well as the overall effect for each subgroup. Negative effect sizes indicate higher amplitude with more autistic traits.



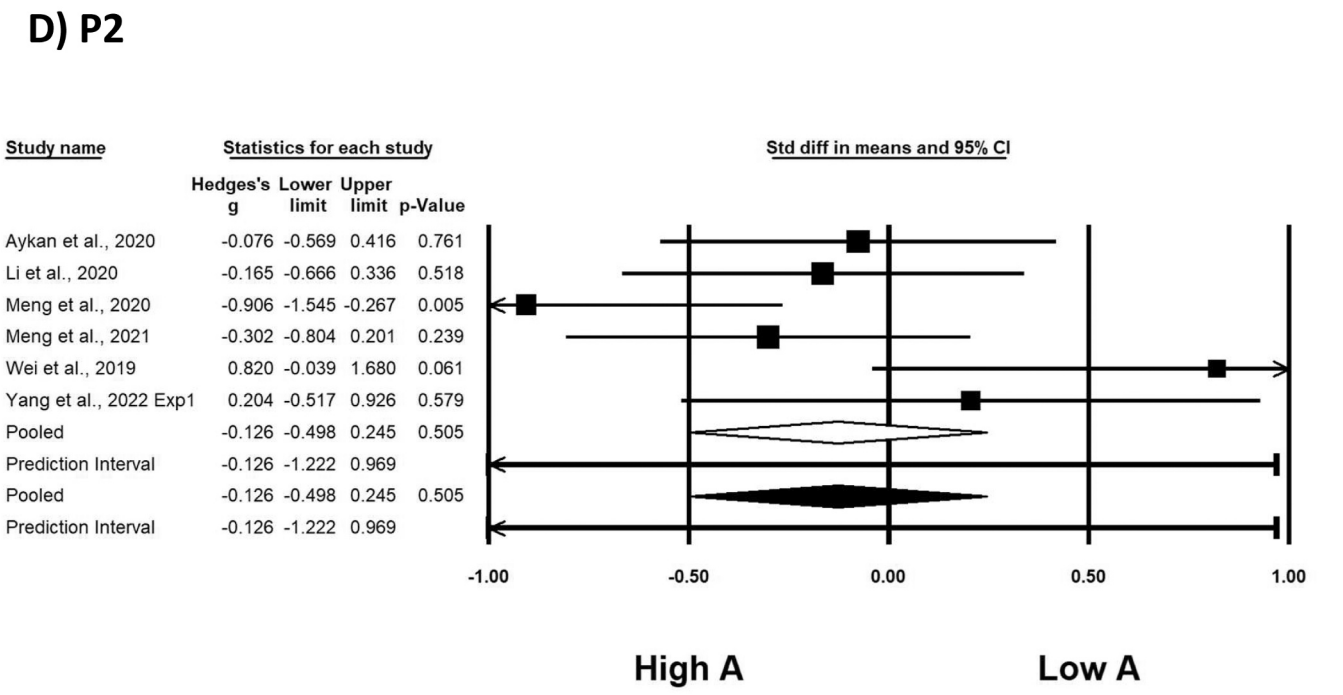


Fig. 2. (*continued*).

[0.10, 0.80], p = .011). The opposite pattern occurred for visual stimuli (g = −0.23, 95 % CI [−0.40, −0.05], p = .011), although the magnitude of the effect was smaller (Fig. 3). The heterogeneity test identified a moderate variance across studies (Q_{38} = 64.21, $p < 0.001$, I^2 = 47.05 %). There was no evidence of publication bias in this analysis (b = 1.35, p = .179, table S1).

Moderation analysis by ERP also revealed a statistically significant but small effect for the component P3b (g = −0.32, 95 % CI [−0.60, −0.04], p = .026), revealing augmented amplitudes for this component in individuals with high autistic traits. In the opposite direction, with a robust effect size, a statistically significant difference was found for the Late Negative Component, LNC (g = 0.64, 95 % CI [0.25, 1.04], p = .003). However, this analysis only included three samples with 95 subjects. Forest plots for P3, N400, and LPC can be found in Fig. 4. Moderation analyses further revealed that higher autistic traits mean scores revealed larger negative effects (table S2 and Fig. S1). No other moderation analysis was statistically significant (all $ps > .137$, tables S3, S4).

4. Discussion

This meta-analytical review represents a pioneering effort to consolidate existing knowledge by comprehensively summarizing the modulation of amplitude in a diverse range of event-related potential (ERP) components concerning autistic traits in the adult population.

The current work included community samples to better apprehend subclinical variations of autism traits, and both early and late ERP encompassing various components and tasks. Statistical differences were observed in ERP amplitudes during the later stages of brain processing, whereas no distinctions were found in the early latency ERP.

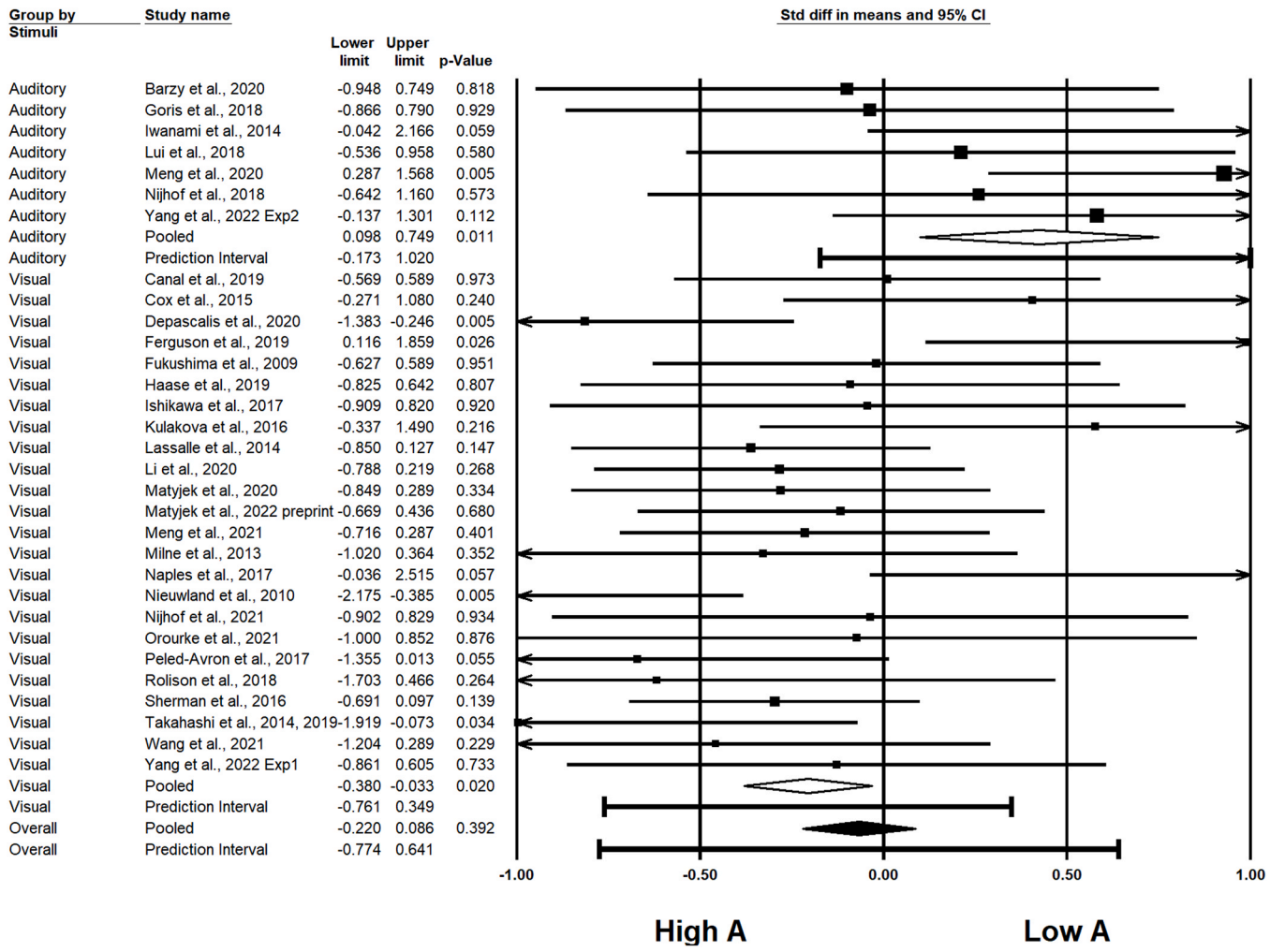


Fig. 3. Forest plot for meta-analysis of ERP amplitude grouped by visual and auditory stimuli. Each study is identified by study name and Hedges' g values, 95 % confidence intervals, and p-values are reported, as well as the overall effect for each subgroup.

The moderation analysis revealed two interesting findings in late components: 1) higher amplitudes for visual stimuli and reduced amplitudes in auditory stimuli, and 2) P3b stood out as the main component associated with autistic traits in a positive direction. These results will be explored in more detail in the following sections.

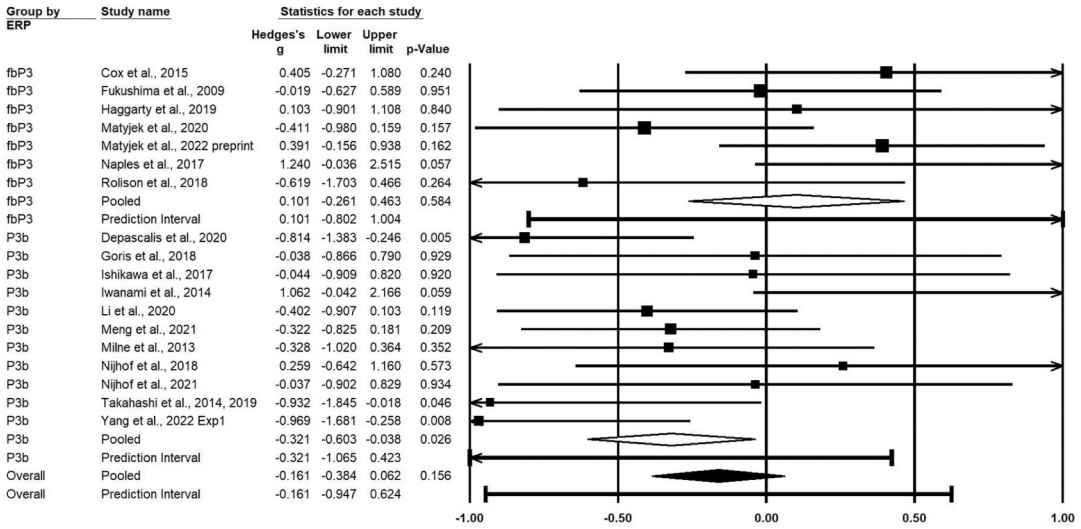
4.1. Visual and auditory stimuli

This review revealed an interesting opposite pattern of ERP modulation in visual and auditory stimuli at the later stages of brain processing (i.e., from 300 ms). Late ERPs were reported to show higher amplitudes for visual stimuli and reduced amplitudes for auditory stimuli. This pattern of findings was exclusive for late ERP and did not reach significance for early ERP.

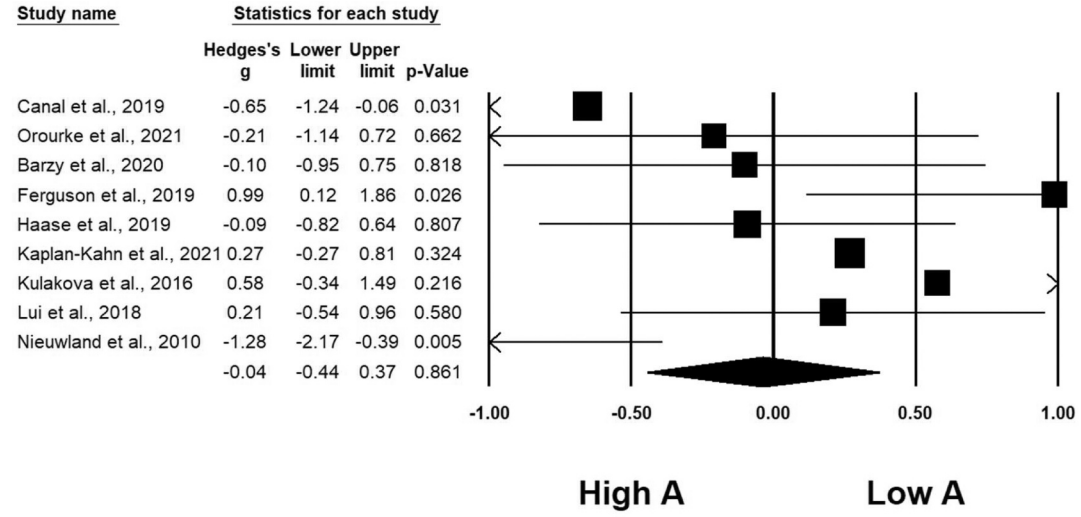
The findings for visual stimuli steam from 25 studies and suggest that late ERP components can covary with increased severity expression in autistic traits. This result seems to be in line with the most recent advances in the field of neuroscience and ASD, namely those framed under the Predictive Processing Framework (PPF).

The PPF considers the brain an inference engine that works according to Bayesian probability updating (Aitchison & Lengyel, 2017; Friston, 2010). Based on prior experiences, the brain actively develops an explanatory model of the world that is used to anticipate inputs – the so-called priors. If the model is accurate, then it correctly predicts sensory inputs. If not, the prior needs to be updated, and a prediction error occurs. From this perspective, a prediction error can be characterized as the difference between the brain's predictions and sensory inputs (Friston, 2010). In this sense, this framework proposes that we refine our priors and internal models of the world by combining initial predictions with incoming sensory information. Whether priors become updated depends on how reliable the input is. Noisy stimuli will be less likely to change the initial prior, so we can make sense of the world by rapidly interpreting noisy stimuli based on prior experiences. Moreover, the way priors are updated can depend on individual differences that influence brain mechanisms. Alterations in prediction error processing and prior updating have been applied to understanding the neurocognitive mechanisms and the heterogeneity of symptoms in ASD. Autistic traits appear to relate to over-precision when processing sensory inputs, even when sensory stimuli are noisy and should not be trusted – which prevents the correct update of priors (Andersen, 2022; Van de Cruys et al., 2014). Because people with ASD are constantly trying to use small and noisy prediction errors, they fail to update their expectations of the world and are more likely to experience a sensory overload (Andersen, 2022; Pellicano & Burr, 2012; Van de Cruys et al., 2014). Although these abnormalities can impair adjustment to the environment, it can explain superior performance on visual and auditory tasks (Cribb et al., 2016; Stewart et al., 2018), especially in tasks requiring sensory-discrimination abilities. For example, several studies have reported lower susceptibility to visual illusions in ASD (Happé, 1996; Joseph et al., 2009; Karvelis et al., 2018; Plaisted et al., 1998). As such, and in light of the results of the current meta-analysis, higher late ERP amplitudes found for visual stimuli in high autistic traits can reflect the

A) P3



B) N400



C) LPC

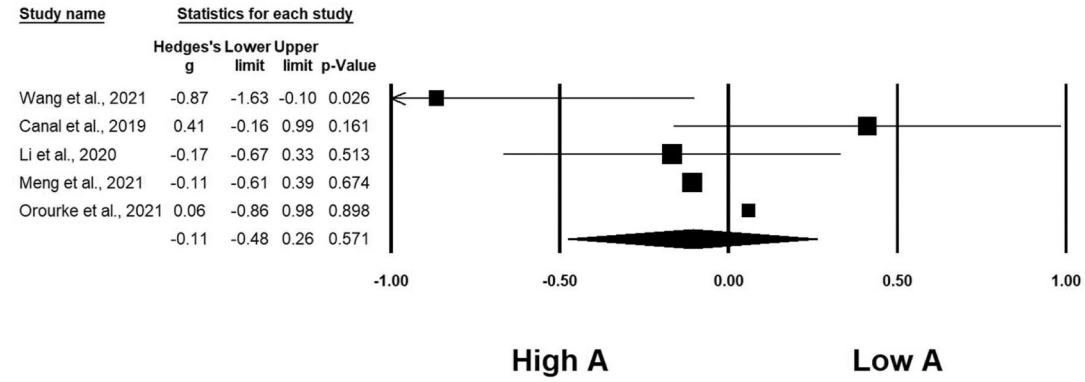


Fig. 4. Forest plot for meta-analysis of ERP amplitude grouped by ERP component. Each study is identified by study name and Hedges' g values, 95 % confidence intervals, and p-values are reported, as well as the overall effect for each subgroup. Negative effect sizes indicate higher amplitude with more autistic traits.

higher prediction error influx – which can then underlie superior visual abilities found in ASD.

However, one should acknowledge that the opposite pattern was found for auditory stimuli in autistic traits (i.e., reduced late ERP components), which is curious considering that PPF assumptions apply to both visual and auditory domains and superior performance is also observed in auditory tasks. When examining seven studies, it was reported that autistic traits were associated with reduced late ERP amplitudes in response to auditory stimuli, which contrasts with the hypersensitivity to noises commonly observed – and that could explain over-precision in prior updating and consequent reliance on noisy stimuli (Andersen, 2022; Van de Cruys et al., 2014). Superior performance in ASD, such as perfect pitch, has been previously described (Stanutz et al., 2014). Still, results are more inconsistent in the auditory domain with impaired performance in auditory tasks being reported as well in the ASD literature broadly (for a review see Lin et al., 2017). This difference between the consistency of impairments in auditory and visual processing at a cognitive level has been described in ASD, with more impairments found indeed in the auditory domain (Courchesne, 1987; Jeste & Nelson, 2009), Specifically, in the ERP literature conflicting results exist, such that smaller, equal, or larger amplitudes have all been described in ASD groups for distinct ERP components (Jeste & Nelson, 2009). A review of auditory processing in Autism by O'Connor (2012) sheds light on this topic and offers a conciliatory hypothesis. It remains possible that auditory dysfunctions in ASD are restricted to more complex stimuli and demanding tasks, while at a lower level of processing with simple stimuli, autistic individuals are expected to outperform. Considering that most of the studies included in the auditory subgroup analysis (five of seven) resorted to complex stimuli, our results may be representative of the difficulties expected to be found in autistic traits within complex and demanding processing categories. So, ultimately, different mechanisms related to sensory complexity can operate to produce distinct outcomes. Another possibility is that these results are task-dependent, such that tasks more consistent with the PPF framework (i.e., those including priors and novel or unexpected stimuli, such as the oddball tasks) are better for testing its assumptions.

4.2. Late ERP components

P3b emerged as the second most frequently reported component in 11 studies, trailing only behind P1, which was analysed in 14 studies. P3b covaried in the function of autistic traits such that higher amplitudes of this late component were particularly observed in higher trait scores. This result is in line with the PPF proposals for ASD. PPF has been used to explain MMN and P3b amplitude reductions for standard/expected stimuli and enhanced amplitudes for target or rare features in ASD (Van de Cruys et al., 2014) – which reflects the opposite pattern of findings for what is expected in healthy samples (Chennu et al., 2013). Increased amplitudes of these components for novel or rare stimuli are believed to represent an alteration in prediction error codification when considering the expected and incoming stimuli. As such, our results are in the same line of enhanced prediction errors in ASD as assessed by P3b modulation.

However, considering the differences mentioned in the previous section, regarding the stimuli modality, we can not dissociate this analysis from the sensory modality. We have to consider that within the 11 studies found with the P3b component, 8 included visual stimuli, while two were auditory and one somatosensory. The increased weight of visual tasks could have contributed to the differences found in this component, considering what was previously discussed.

In another direction, the MMN, a component also known to index prediction error, did not reveal any amplitude modulation with autistic traits. Nonetheless, we have to consider that only five studies included this component, which might not be sufficient to find robust and significant effects. In addition, the MMN is mainly elicited by auditory stimuli and much of the literature regarding this component describes it as auditory (Luck, 2014). Its visual counterpart, the vMMN, has been described in response to similar paradigms as the auditory MMN (e.g., novel oddball tasks) (Kimura et al., 2010) but only one study, out of 5, included the vMMN, making it impossible to analyse the impact of stimuli modality in this analysis. Conversely, the divergence in patterns between this earlier component and P3b suggests that bottom-up information processing remains unaffected, while the impairment lies in the ability to integrate higher-level expectations, as reflected by P3b. This is reinforced by noting that the distinct differences between individuals with high and low autistic traits were exclusively identified during the analysis of the later components.

Another late component that revealed differences in amplitudes as a function of autistic traits was the LNC, with lower amplitudes found for higher autistic scores. Nonetheless, this result needs to be considered carefully, as it was based on only three studies with auditory stimuli. In this sense, this result aligns with a high-level auditory processing impairment that can be translated into smaller amplitudes in a 300–700 ms time window at prefrontal topographical sites. This contrasts with the result of P3b, which occurs in a similar time window but is generally measured in areas around the electrode Cz/Pz. This result may once again reflect variations based on sensory modality.

4.3. Limitations and future directions

Some of the limitations of this meta-analysis need to be addressed. Namely, it is essential to acknowledge the extensive nature of the statistical testing, involving 14 different ERPs and various experimental conditions, such as visual and auditory stimuli, among others. Despite the meticulous approach to testing, certain results lose significance after correction for false discovery rate (FDR, supplemental material). This is also due to the heterogeneity found for early and late ERP subgroup analysis. Moderate to large variances across the studies were identified. The variety of components included in each analysis possibly contributed to this variance. The number of studies included in some moderation analyses, particularly for ERP nomenclature, might have been underpowered to find differences. It should also be taken into consideration the vast variations in study design, participant characteristics, and measurement tools across included studies which can complicate the integration of results. While efforts were made to address these differences through subgroup analysis, certain methodological distinctions persisted and must be taken into account.

Nonetheless, the current results may inform future direction in the field. Future studies should consider the stimuli modality and complexity as significant moderators to uncover impairments and reports of superior performance of lower and higher-level brain processing. Unfortunately, we could not include a meta-analysis of somatosensory stimuli as only one study explored this type of stimuli. It would be interesting for future studies to explore somatosensory stimuli and understand if this pattern of higher and lower amplitudes is exclusive to visual and auditory stimuli. Also, building specific tasks that require an expectation and the violation of that expectation could help us understand if the Predictive Processing account for ASD is accurate. In addition, more studies with larger samples and focusing on dimensional approaches to Autism are important to understand how the brain's electrophysiology can reflect the strength or intensity of ASD manifestations. Notably, it is worth highlighting that no studies have specifically investigated the heritability of these ERPs and their genetic correlations with autistic traits, for example, in the context of first-degree relatives. Finally, it would be interesting to understand if enough data on the P3b component is available to replicate this analysis with the clinical ASD population.

5. Conclusion

In conclusion, this meta-analytical review represents a comprehensive effort to consolidate knowledge on the modulation of amplitude in

various event-related potential (ERP) components related to autistic traits in adults. The analysis highlighted intriguing findings, particularly the opposite modulation patterns for visual and auditory stimuli in late ERP components. These results align with the Predictive Processing Framework, offering insights into sensory processing abnormalities associated with autistic traits. However, the complexity of auditory processing in autism, especially in the context of more demanding tasks, remains a topic of interest and warrants further exploration. Noteworthy, the component P3b displayed associations with autistic traits, providing valuable insights into the neural correlates of possible alterations within the predictive processing framework. The limitations, including the extensive nature of statistical testing and variations in study design, underscore the need for cautious interpretation. Despite these limitations, this meta-analysis sets the stage for future research directions, emphasizing the importance of stimuli modality, task complexity, and a dimensional approach to autism.

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CRediT authorship contribution statement

Silveira Celeste: Supervision, Writing – original draft. **Pasion Rita:** Conceptualization, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing, Methodology. **Sempf Frederieke:** Formal analysis, Investigation, Writing – original draft. **Ferreira-Santos Fernando:** Methodology, Supervision, Writing – original draft, Writing – review & editing. **Mazer Prune:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Macedo Inês:** Data curation, Investigation, Methodology. **Garcez Helena:** Data curation, Investigation, Methodology.

Declaration of Generative AI and AI-assisted technologies in the writing process

The author(s) did not use generative AI technologies for the preparation of this work.[1]

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2024.108758.

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