Electrophysiological Approaches in the Study of the Influence of Childhood Poverty on Cognition

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Abstract The influence of adverse environmental conditions on the organization and reorganization of the brain structure and function involves distinct neural systems at different levels of organization. Electroencephalographic (EEG) measures provide precise evidence on the temporal sequence in which relevant cognitive processes occur. Here, we offer a systematic review of EEG studies on the influence of childhood poverty on cognitive development. The paradigms used focused primarily on correlates of inhibitory control, selective attention, and unrelated task-event activity. Eighteen studies reported differences related to socioeconomic disparities, including (a) discrepancies in neural markers of interference control and early auditory sensory processing and (b) delays in the maturation of brain oscillations in frontal regions. Overall, EEG techniques appear to have predictive power over cognitive and academic performance of children. Therefore, EEG markers may be useful to evaluate the efficacy of interventions aimed to enhance cognitive development in children facing unfavorable social conditions.

Keywords EEG • ERP • Socioeconomic status • Childhood poverty • Cognitive development

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1 Introduction

Early experiences influence emotional, cognitive, social, and learning-related developmental processes, which play an important role in children's educational and social integration opportunities during their first two decades of life [1–3]. Accruing evidence in the fields of developmental psychology and developmental cognitive neuroscience indicates that during such a period, adverse environmental experiences, associated with poverty, are related to changes in the development of different aspects of cognition at different levels of organization [4–18].

Although its complexity is not always considered adequately, poverty is a highly multidimensional, relational, and dynamic phenomenon. Its influences on cognitive development are given by a set of mediation and moderator factors that are part of the daily experience (see Kwon, this volume). Mediators and moderators involve both individual and contextual factors at different levels of organization. Some of the most important mediators that are postulated in the contemporary literature are (1) prenatal and perinatal health factors; (2) housing conditions; (3) neighborhood characteristics; (4) quality of home and school environment; (5) opportunities for cognitive and learning stimulation at home; (6) parenting and care styles; (7) parental mental health; (8) family, social, and cultural expectations about child development and learning; (9) access to social support networks; and (10) material and symbolic resources of families [13, 19–25]. In particular, the experience of poverty is associated with a set of potential cumulative and interacting risk factors [20, 26], which increase the likelihood of developing negative outcomes later in life [22, 23, 27, 28].

In addition, the impact of these risk factors on cognitive development may vary according to the individual's susceptibility and to the type, number, co-occurrence, and timing of exposure to deprivations [21, 22, 25, 26, 29–32]. Consequently, identifying factors of childhood poverty is a very complex task, comprising various theoretical, methodological, and logistical difficulties which make it difficult to generalize individual experiences. In turn, it is important to implement adequate research designs that can specify what aspects of experience of poverty contribute to individual differences in cognitive development and the efficiency of different neural networks [31], because the evidence suggests that different types of adverse experiences generate different influences on brain development [33, 34]. However, the measures of poverty that are commonly used in current studies on childhood poverty and cognition do not necessarily capture the complexity of the multiple adverse experiences. Moreover, no clear consensus has emerged on what indicators should be used to categorize an individual as poor. Thus, the present work focuses on the ways in which poverty is measured, highlighting the importance of improving our comprehension of childhood poverty as a multidimensional phenomenon in terms of individual experiences. From this perspective, we expect that this approach will contribute to the design of interventions to improve cognitive development.

2 The Neuroscientific Approach

There is an increasing body of neuroimaging evidence on the association between brain structure/functioning and childhood poverty, which indicates that the experience of childhood poverty is related to the activity and anatomical development of distinct brain networks. This evidence points regions implicated in cognitive domains such as language (e.g., left inferior frontal and fusiform gyrus), memory and learning (e.g., hippocampus), executive functioning (e.g., prefrontal cortex), and social-emotional processing (e.g., amygdala) [15, 35–39].

Here, we focus on electroencephalographic (EEG) studies that examine links between neural activity and measures of childhood poverty. These methodologies have the advantage of directly measuring neural activity and capturing cognitive dynamics in the time frame in which cognition occurs [40]. Their high temporal resolution allows tapping into the neural mechanisms engaged at each stage of information processing. For instance, examining the neural systems that underlie a particular cognitive ability can reveal subtle differences along information-processing streams, even in the absence of significant behavioral manifestations (e.g., [41]). This suggests that EEG methods may be helpful for elucidating fine-grained differences in brain processing associated with poverty. In addition, cognitive electrophysiological techniques are noninvasive, robust, fast to compute, applicable to large-scale screening, and much less expensive than other techniques. Such methodological attributes have important implications in building knowledge of cognitive development and the contextual modulation of poverty-related risks. In this sense, cognitive electrophysiology might offer an affordable, massive, and temporally precise approach to reveal cognitive indicators of negative and positive influences related to adverse (e.g., social inequality) and favorable (e.g., intervention programs) contextual experiences.

3 A Systematic Review of the Literature

The present study aimed to analyze the literature about the influences of childhood poverty on cognitive development from the perspective of cognitive electrophysiological explorations and to shed light on how poverty shapes brain function and impacts on cognitive components of behavior. In particular, we address the mechanisms supporting these processes and their association with children's poverty or low socioeconomic status (SES) experience.

After applying the *Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols* (PRISMA-P) methodology for systematic reviews,[1] we identified a total of 18 studies from 12 articles from 5 countries, published between 1990 and 2016—most of them (67%) appearing over the last decade (Table 1).

3.1 Poverty Measures

In general, the studies explored the influence of poverty or low socioeconomic status on neural activity through three primary indicators: income, parental education, and occupation. Either combined or in isolation, these measures are commonly used to index SES. Importantly, the indicators varied among the studies. Some measures estimated low SES using a single variable such as *maternal education* [17, 42, 43] or *family income* [44], although others used both measures [45], or focused on variables based on family income, family income-to-needs ratio, parental occupation, or parental education [46–48]. Others used composite variables combining indexes of parental occupation, parental education, and family income, which were assessed by standardized questionnaires [5, 41, 48–56] (Table 1).

Most of the studies implemented discrete categories with different criteria to divide the measures into separate groups. For instance, when maternal education was used, if the mother had only completed high school education she was generally considered to have a low level of instruction [17, 42, 43]. When family income was used, it was considered either as gross family income [47] or as the percentage of the minimum monthly wage [45]. Finally, parental occupation was determined by one study [47] that used a category scale [57] to make three occupational groups (higher managerial or professional, intermediate and routine/semi-routine, and unemployed over the last 6 months). In turn, other studies implemented singular continuous estimates to explore the relationship between poverty and low SES vari-

[1] Our systematic review is based on the PRISMA-P standard protocol [113] to examine the association between poverty indicators and EEG activity in developmental cognitive studies. The search criteria contemplated: (a) articles published in English without restrictions on the range of the publication dates; (b) studies with an age range between birth and adolescence; and (c) experimental research reporting factors that were related to childhood poverty, EEG measures, and their relationship with cognitive development. Studies were identified by searching electronic databases and inspecting reference lists of articles. This search was applied to the National Library of Medicine's MEDLINE and EBSCO databases, considering the following terms: "SES," "income," "education," "occupation," "poverty," "social vulnerability," "ERP," "EEG," "children," "preschool," "kindergarten," and "school." Three reviewers selected the studies, and any disagreements were solved by consensus. We selected those articles in which the primary purpose was to measure the impact of poverty-related factors on brain and cognitive functioning. Conversely, the ones that were aimed mainly at addressing factors not necessarily associated to poverty (e.g., parental mental health or air pollution), or that were focused on extreme deprivation of these aspects (e.g., undernutrition, maltreatment), were not selected, even though they showed a certain relevance in assessing the impact of childhood poverty. The information that was extracted from each study included (1) sociodemographic characteristics of participants; (2) poverty measures (type, method of measurement, quantity and quality of considered factors); and (3) EEG and cognitive paradigms (amplitude, latency, power spectra of activity through scalp sites, accuracy, and reaction time of behavioral performances).

Table 1 Studies on the relationship between SES and EEG/ERP measures

Study	Participants	Poverty measure	Technique	Paradigm	Findings
Conejero et al. [48]	16–18 mos (*n* = 52)	SES[d] family income-to-need ratio	ERP/ freq. analysis	Error detection task	Large differences in frontal ERN (450–750 ms) and in theta power (300–600 ms after stimuli) among correct and incorrect configurations were, respectively, related to higher family SES and higher family education
		Parental occupation and education			SES in general, and parental education in particular, contributed to individual differences in the amplitude of ERN and associated theta power
Isbell et al. [51]	3–5 yrs (*n* = 124)	SES[b]	ERP	Auditory selective attention task	Early (100–200 ms) differential activation (attended-unattended story) at fronto-central sites was positively correlated to nonverbal IQ scores
Neville et al. [52]	3–5 yrs (*n* = 141)	SES[b]	ERP	Auditory selective attention task	Parent-based training showed more changes in the neural response (100–200 ms) underlying selective attentional processes
Ruberry et al. [44]	3–6 yrs (*n* = 118)	Family income	ERP	Go/no-go task and flanker task	Absence of significant correlations between ERP and income. Significant correlations between ERP and cognitive performance (executive control). ERP was associated with differential activity (N2, go minus no-go; P3, congruent minus incongruent) underlying the performance of go/no-go and flanker tasks

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Table 1 (continued)

Study	Participants	Poverty measure	Technique	Paradigm	Findings
Stevens et al. [43]	3–8 yrs (n = 30)	Maternal education	ERP	Auditory selective attention task	The refractory effect was faster in the attended story in children with higher maternal education, while lower maternal education children had similar refractory effects to attended and unattended stimuli
Stevens et al. [17]	3–8 yrs (n = 32)	Maternal education	ERP	Auditory selective attention task	Lower maternal-education children showed responses of greater amplitude in the 100–200 ms time-window to task-irrelevant stimuli at fronto-central scalp regions
Kishiyama et al. [41]	7–12 yrs (n = 26)	SES[a]	ERP	Visual detection task/novelty oddball paradigm	Lower SES children showed reduced P1 and N1 components to task-irrelevant stimuli at parieto-occipital leads and reduced N2 to novel stimuli at central scalp regions
D'Angiulli et al. [49, 50]	11–14 yrs (n = 28)	SES[b]	ERP/ freq. analysis	Auditory selective attention task	Early (100–400 ms) and late (600–800 ms) differential activation (attended-unattended auditory stimuli) was greater in higher SES children over mid-frontal cortical regions. However lower SES children had more mid-frontal and frontal theta power to the unattended than attended tones between 200 ms and 700 ms

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Table 1 (continued)

Study	Participants	Poverty measure	Technique	Paradigm	Findings
D'Angiulli et al. [49, 50]	13 yrs ($n = 28$)	SES[b]	ERP/ freq. analysis	Auditory selective attention task	Lower SES children showed an increase in selectivity of attention (Nd amplitude) concomitant to an increase in post ERP cortisol levels, whereas no such relationship was observed in higher SES children
D'angiulli et al. [5]	13 yrs ($n = 28$)	SES[b]	ERP/ freq. analysis	Auditory selective attention task	Children from lower SES backgrounds showed a right activation asymmetry at the mid-frontal scalp site in theta band, whereas higher SES showed the opposite pattern
					Individual mid-frontal right attentional activation was associated with individual differences across SES rank, task-dependent cortisol reactivity, and increase in boredom at the start of the task
Skoe et al. [42]	14–15 yrs old ($n = 66$)	Maternal education	ABR	Passive listening paradigm	ABRs from lower maternal education adolescents showed a lower consistency of response, a weaker encoding of speech and greater noisier activity
Brito et al. [46]	At birth ($n = 66$)	Parental education, family income, family income-to-needs	freq. analysis	Sleep (~10 min)	EEG spectrum was not correlated to SES. However, it was associated with cognitive performance (memory and language) at 15 months

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Table 1 (continued)

Study	Participants	Poverty measure	Technique	Paradigm	Findings
Tomalski et al. [47]	7–8 mos (n = 55)	Gross family income or maternal occupation	freq. analysis	Watching videos	Infants from lower-income families and mother occupation had lower frontal gamma AP
Otero [55]	20–30 mos (n = 50)	SES[c]	freq. analysis	Sleep (~30 min)	Lower SES children showed significantly higher delta power in all scalp regions, lower alpha power in frontal, central and occipital regions
Otero [54]	4 yrs (n = 42)	SES[c]	freq. analysis	Eyes closed (~10 min)	Children from lower SES showed significantly higher total power over anterior sites, higher power in lower delta and theta bands over frontal leads, and lower alpha power over frontal, occipital and temporal sites
Otero et al. [53]	5–6 yrs (n = 42)	SES[c]	freq. analysis	Eyes closed (~10 min)	Lower SES children showed at 5 years higher power in theta and delta bands over frontal areas and lower power in alpha band, especially over posterior areas. At 6 years of age, differences remained the same for theta and alpha, respectively, at frontal regions and temporal-occipital scalp regions
Harmony et al. [45]	6–13 yrs (n = 118)	Maternal education and income per head	freq. analysis	Eyes closed	Lower SES children had higher power in delta, theta and beta bands over frontal regions. Moreover, lower power in alpha band over frontal, temporal and occipital regions were observed in lower SES children

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Table 1 (continued)

Study	Participants	Poverty measure	Technique	Paradigm	Findings
Tomarken et al. [56]	12–14 yrs (n = 39)	SES[b]	freq. analysis	Counterbalanced eyes open and eyes closed	High-risk children had higher power in alpha band in left relative to right frontal areas. SES, but not risk status, significantly predicted asymmetry measures

ABR auditory brainstem response, freq. analysis band frequency analysis, *ERP* event-related potential, *SES* socioeconomic status
[a]MacArthur sociodemographic questionnaire
[b]Four-factor index of social status [115])
[c]Questionnaires from [114])
[d]Z-transformed scores based on parental occupation, parental education, and family income-to-need ratio

ables and EEG measures, instead of collapsing the information into discrete categories [42, 44, 46, 48, 56].

The methods used to measure poverty and SES differ among studies in terms of how scores are calculated and the quantity and quality of involved factors. It is thus unclear whether implemented poverty measures across studies capture similar underlying factors and how this impacts on their comparability. Importantly, each poverty indicator is related to the presence or absence of resources that may influence brain structure and functioning in different ways [31, 33, 34, 58]. For example, it has been shown that distinct socioeconomic factors are associated with specific features of neuroanatomical development, such as surface area [37]. In particular, parental education and family income seem to be associated in different ways with brain areas that are considered critical for language, memory, and cognitive development. Noble and colleagues [37] found that family income was logarithmically related to brain surface areas, but parental education had a linear association with those areas.

These findings highlight the need for the implementation of experimental designs that allow us to explore the specific influence of poverty and low SES indicators on brain structure and function separately. Most EEG/ERP studies tend to underestimate the fact that these poverty indicators are based on different conceptual frameworks related to cognitive outcomes. However, the few studies that examined poverty indicators separately found null correlations or similar associations between EEG/ERP patterns and each indicator [46–48]. Moreover, the use of one poverty or low SES indicator, or a set of poverty or low SES indicators, does not contemplate the temporal dynamics in the experience of childhood poverty. Adverse experiences related to poverty and their influence on brain development are no stable across the first two decades of life [8, 59]. Furthermore, the correlation between poverty and low

SES indicators and EEG/ERP outcomes could also be the result of the combination of other individual differences in temperament and environmental susceptibility [34], which in general are not considered in the reviewed studies.

In sum, electrophysiological approaches to study the influences of poverty on brain functioning apply classic unidimensional indicators not considering the variability of different aspects of the adversity experiences (as shown by distinct indicators), and the dynamic nature of changes during development as well. This creates a partial characterization of the individual experience of poverty or low SES, and overlooks the complex scenario comprised of mediation mechanisms that support the correlation between poverty constructs and EEG/ERP outcomes [33, 34]. These issues constitute a fertile field for the interdisciplinary exploration between neuroscience and the social sciences to contribute to the design of childhood poverty and low SES indicators that could help deepen the knowledge of their associations and mechanisms.

3.2 Electrophysiological Paradigms

Two major measures were implemented across the 18 EEG studies reviewed: (a) frequency analysis of baseline EEG activity and (b) ERPs. In seven articles, baseline EEG activity was recorded to assess overall differences in the patterns of EEG between SES groups through a broadband frequency analysis [45–47, 53–56]. This unrelated task-event activity is generally utilized to infer overall characteristics of neural architecture. Broadband frequency analysis allows quantifying oscillatory electrical activity at different frequencies. Although baseline EEG recording intends to represent a general unrelated task-event activity, it could be acquired using different paradigms and experimental conditions (e.g., resting state, ERP). This is inevitable when performing experiments at different developmental stages, but it poses an additional difficulty when comparing through them. In many studies presented in this chapter, the children remained awake with their eyes closed [45, 53, 54], and this could be counterbalanced with “open-eyes” trials [56]. In the other two studies, resting state was acquired during sleep [46, 55]. Finally, in one study, the children watched videos of toys and interacting faces [47] (Table 1).

In the remaining 11 articles, electrical activity that was associated with a perceptual or cognitive task was recorded (ERPs) [5, 17, 41–44, 48–52] (Table 1). The activity that was related to the tasks was also used to perform a spectral power analysis in each trial before averaging them [5, 48–50].

The paradigms implemented in the reviewed ERP studies were mainly aimed to explore executive control processes (Table 2). First, three different tasks were implemented to examine neural mechanisms of selective attention: (1) a *nonspatial auditory attention task*, in which participants had to give an overt response [5, 49, 50]; (2) a *spatial auditory attention task*, in which no active response was required [17, 43, 51, 52]; and (3) a *novelty oddball paradigm* that was implemented to assess visual selective attention [41]. Second, the neural mechanisms that underlay different inhibitory control processes were evaluated in two separate tasks [44]: a novel *go/no-go task* was designed to assess mainly the response inhibition, and a modified *flanker task* was administered to evaluate fundamental control functions interference. Third, brain mechanisms that were involved in error detection processes were investigated through a passive paradigm [48]. Finally, a passive listening task was used to measure auditory brainstem responses (ABRs) [42]. Different aspects of the ABRs were examined collectively under the term "auditory neural acuity." Authors defined this term as "the nervous system's ability to resolve and reliably transmit fine-grained information about acoustic signals within the environment" [42] (Table 2).

3.3 ERP Studies on Socioeconomic Status Throughout Development

To investigate the effect of different developmental environments on brain functioning, investigators have examined prefrontal-dependent functions and auditory brainstem processing using ERP. Conejero et al. [48] conducted a study in toddlers (16–18 months) aimed to investigate whether neural mechanisms involved in error detection were related to SES variables. Electrophysiological responses (ERP and oscillatory neural activity in theta band) from different conditions (correct, position error, conceptual error) of an error detection paradigm were measured. Briefly, the results showed a significant increase in the amplitude of the error-related negativity (ERN; 450–750 ms poststimulus onset) and in theta power, within 300–600 ms after stimulus onset, and over the fronto-central scalp regions for incorrect trials in all groups. Correlational analysis showed that these electrophysiological measures were also associated with SES. Specifically, a decrease in expected differences in ERN between correct and incorrect configurations were related to lower family SES and lower family education, and a decrease in differences in theta power between correct and incorrect configurations was related to lower family education. The authors reasoned that adverse environmental conditions related to low SES might affect the executive attention network in early stages of cognitive development. This argument is supported by evidence that shows that both ERN and frontal theta oscillations were associated with other executive attentional-related tasks [60–62] and the activity of the anterior cingulate cortex [63, 64], which is an important node of executive network that is involved in regulation of conflict [65]. Nevertheless, a reduced response of error-related signals in children from lower SES families may indicate a poorer activation of the executive attention network that is related to conflict detection, or a debilitated representation of stimulus configurations, or both.

Executive attentional processes that are related to inhibitory control were explored with a large sample that included children aged 3–6 [44]. The researchers evaluated whether differences observed in executive control tests that were related to family income could be accounted for by differences in the underlying neural processes. Specific ERPs were calculated at frontal (N2) and parietal (P3) scalp sites in two inhibitory control tasks (*flanker task* and *go/no-go task*). Both income and ERP measures were associated separately with behavioral performance on an executive control battery. On the one hand, lower income was correlated with poorer performance. These results are in line with prior behavioral findings that show that children from poor homes present a lower performance in executive control task [28, 66, 67]. On the other hand, better performance on the executive control battery was correlated with (1) larger differences in activity on N2 for go minus no-go trials (*go/no-go task*), (2) larger differences in activity on P3 for congruent minus incongruent conditions (*flanker task*), and (3) smaller positive P3 amplitude for incongruent trials. Importantly, nonsignificant correlations were found between the amplitude of ERPs on these inhibitory control tasks and family income [44]. One possible explanation is related to the design of the ERP tasks. For instance, the performance measured in computerized ERP paradigms often has a high level of accuracy, because these tasks are programed intentionally not to be over-demanding to keep the underlying electrophysiological activity reliable. Therefore, SES effects might not be observed at the neural level because the task was not sensitive enough (had less power) to capture the predicted association with the neural mechanisms that underlie ERP. Moreover, executive control performance was associated separately with ERP and income. These significant associations might be noticeable because a specific test battery collects great amounts of single tasks assessing different dimensions of the complex evaluated function; hence, it is more reliable in capturing individual differences in the entire sample. Another explanation, suggested by Ruberry et al. [44], is that the observed income disparities in executive control performance might be related to other mechanisms than executive attention and inhibitory control that were assessed by *go/no-go* and *flanker tasks*.

Several studies have reported differences in ERP measures of selective attention between children from poor and nonpoor families [5, 17, 41, 43, 49, 50]. Kishiyama et al. [41] examined neural signatures of visual selective attention and performance on executive function tests in relationship to SES, in children between 7 and 12 years of age. During the selective visual attention task, the children were asked to respond upon detection of the low-probability targets that were embedded in streams of the task-irrelevant stimuli (novel or high-probability standard stimuli). Although both SES groups had similar amplitude to target stimuli, lower SES children had a decreased amplitude of parietal P1 and N1 to standard stimuli, and a decreased amplitude of fronto-central N2 to novel stimuli than the higher SES counterparts (see Table 2 for details). These results indicated that electrophysiological measures of attention were reduced in lower SES children to task-irrelevant and novelty stimuli.

Stevens et al. [17, 43] examined the effects of maternal education level (HME, higher maternal education; LME, lower maternal education) on a *selective auditory attention task* in children 3–8 years old. The ERPs were calculated in relation to the probe stimuli that were superimposed to both attended and unattended channels (i.e., attended and unattended narratives that were administered in the right and left ear) (Table 2). Although children remembered both stories equally well, brain activity differed between groups over central and frontal scalp sites. Specifically, both

Table 2 ERP paradigms

Paradigm	Studies	Experimental design	ERP components
Nonspatial auditory attention task	D'Angiulli et al. [5, 49, 50]	*Instructions*: Respond as fast and accurately as possible to one of four tones presented binaurally. The relevant tone was indicated at the beginning of the experimental session	Subtraction of the maximum negative deflection, between attended nontarget duration tones and unattended nontarget duration tones
		Stimuli: Tone, {800 Hz, 1200 Hz}; duration {100 ms, 250 ms}	
		Interstimulus interval: 1 second	*Latencies*: {100–400 ms and 600–800 ms}
		Conditions: Target tones, 10%; unattended target tones, 10%; attended nontarget tones, 40%; and unattended nontarget tones, 40%	*Scalp sites*: {Fronto-central}
Spatial auditory attention task	Isbell et al. [51], Stevens et al. [15, 43], Neville et al. [52]	*Instructions*: Attend to a story presented from either the left or the right speaker, while ignoring the other story -presented on the other side. The two stories always differed in story content and narrator voice (male/female). Small images from the attended story together with small arrow pointing toward attended channel were displayed on a monitor	Mean amplitudes were compared between probe stimuli presented on the attended and unattended channels
			Latencies: {100–200 ms}
		Stimuli: Linguistic and nonlinguistic probe stimuli {70 dB} superimposed on both narratives; duration, {100 ms}	*Scalp sites*: {Fronto-central}
		Interstimulus interval: {200 ms, 500 ms, 1000 ms}	
		Condition: Attended vs. unattended	
Selective visual attention task	Kishiyama et al. [41]	*Instructions*: Detect the low-probability targets embedded in streams of task-irrelevant stimuli (novel and standard stimuli)	For standard stimuli P1 and N1 components were quantified
			Latencies: {50–150 ms, 100–250 ms}
		Stimuli: Black triangles {target, standard} and digitized color images {novel}. The target triangles were tilted to the right relative to upright standard triangles	For target and novel stimuli P2 and N2 were computed
			Latencies: {50–250 ms, 100–350 ms}
			Scalp sites: {Parieto-central}
		Duration: {250 ms}	
		Interstimulus interval: {1000 ms}	
		Condition: Target, 10%; novel, 15%; standard, 75%	

(continued)

Table 2 (continued)

Paradigm	Studies	Experimental design	ERP components
Go/no-go task	Ruberry et al. [44]	*Instructions*: Press a button when the target changed their original color to blue	For each task condition N2 and P3 components were quantified
		Stimuli: Frog and fish displayed randomly on the screen {flickered at 3 Hz and 5 Hz}; duration, 1200 ms	*Latencies*: {250–400 ms, 400–700 ms}
		Conditions: 25% Were "go trials" in which target stimuli changed their color and children had to press the button, 25% "no-go trials" in which distractor stimuli changed their color and was not required to respond, 50% were "standard trials" in which neither stimuli changed their color	*Scalp sites*: {Frontal, parietal}
Flanker task	Ruberry et al. [44]	*Instructions*: Pay attention to the center target fish and to press the button that matched its direction	For each task condition N2 and P3 components were computed
		Stimuli: Row of five fish centered in the middle of screen; duration, 5000 ms	*Latencies*: {200–400 ms, 400–700 ms}
		Conditions: Congruent: 50%, The flanker fish faced in the same direction as the center fish	*Scalp sites*: {Frontal, parietal}
		Incongruent: 50%, The flanker fish faced the opposite direction of the center target fish	
Error detection task	Rueda et al. [76]	*Instructions*: Pay attention to the progressive completion of puzzles presented on a computer screen	Errors vs. correct contrasts of mean amplitude of ERN component were computed. Further, time-frequency analysis was conducted (theta power)
		Stimuli: Three-piece puzzles of cartoon animals	*Latencies*: ERN {120–160 ms, for adults; 459–750 ms, for toddlers}
		Conditions: Correct completion: 33.3%	*Scalp sites*: Mid-frontal
		Incorrect completion (position error): 33.3%	
		Incorrect completion (conceptual error): 33.3%	

(continued)

Table 2 (continued)

Paradigm	Studies	Experimental design	ERP components
Passive listening task	Skoe et al. [42]	*Instruction*: Attend to a movie and ignore the stimulus that was presented at a rapid rate to the right ear *Stimuli*: Syllable "da" {80 dB}; duration, 63 ms *Rate of presentation*: {10.9/s}	ABRs were passively collected from the stimuli presentations. The consistency along the experimental session, the extent on which the stimulus is represented in the response, and the noise level in the response were examined from ABRs

groups had larger positivity within 100–200 ms of the probe onset in the attended versus unattended channel, but HME had a smaller amplitude of response to probes in the unattended channel than LME [17]. In other words, there were no group differences in the ERP response in the attended channel, but the LME group exhibited a higher amplitude response to the probes in the unattended one. Authors interpreted this pattern of activity as indicative of a reduced ability to filter irrelevant information (i.e., to suppress the response to ignored sounds) in the LME group. Moreover, between-group discrepancy in selective attentional processing was also evident when stimuli were presented at fast rates that caused an auditory refractory effect [68]. Specifically, LME had a similar refractory period effect to both attended and unattended stimuli. The difference in the amplitude of the neural response for stimuli that was presented at inter-stimulus intervals of 500 versus 1000 ms was not significant under either task condition, which suggested full recovery regardless of the direction of selective attention. In contrast, children with HME exhibited the same pattern only in the attended channel, which suggested that full recovery was affected by the direction of selective attention. In other words, auditory refractory effects between children with HME and LME differed specifically for the unattended stimuli [43].

Similar attentional differences related to SES, both in ERPs and spectral analysis, have been found by D'Anguilli et al. in a series of studies using a *nonspatial auditory attention task* [5, 49, 50] (Table 1). Adolescents who were 11–14 years old were instructed to attend and respond to a specific pitch tone (attended channel) and to ignore tones with the other pitch (unattended channel). Whereas higher SES children showed greater ERP differentiation between attended and unattended auditory stimuli, this differentiation was small or absent in lower SES children. This pattern was found over mid-frontal cortical regions at early (100–400 ms) and late (600–800 ms) stages of processing. Consistent with the study by Stevens et al. [17], these results suggested that low SES children may process the irrelevant information differently, paying equally attention to the distracting and target stimuli. Moreover, in the spectral analyses from auditory selective attention task, they showed that a lower SES background was associated with right activation asymmetry for the theta band over mid-frontal sites, and higher theta power was associated with unattended (irrelevant) stimuli compared to attended (relevant) stimuli, but the opposite pattern was related to higher SES environments [5, 49, 50]. Importantly, low and high SES children performed behaviorally similarly, despite the fact that they exhibited different neural responses. Thus, the authors suggested that lower SES children have a differential processing "preference." In other words, they suggested that the last may also attend to distractors that allocate additional attentional resources to task-irrelevant information (higher theta power to unattended stimuli) and, thus, they perform attentional tasks like their higher SES counterparts exert more effortful control (i.e., higher right theta over mid-frontal sites).

Combining the results of these selective attention studies, it appears that differential activation patterns are involved in control attentional processes, especially in early stages of information processing between children with different SES. These findings highlight the need to design more specific types of paradigms to elucidate which attentional control mechanisms might explain these findings. In fact, undifferentiated activity between relevant and irrelevant information could be due to a greater susceptibility to attention, capture by irrelevant items, and a slower attentional disengagement from distractors [69]. Moreover, research efforts should focus on identifying effects and intervening mechanisms that contribute to the association between poverty measures and these attentional patterns. It is plausible that children from poor homes may adopt alternative strategies due to an adaptive response toward the stressful environmental settings that characterize poor homes and neighborhoods, to anticipate potentially challenging, negative, or threatening situations [20, 70]. Poor children could have learned to maintain greater sensitivity toward what surrounds them (general sustained attentional response), which may be associated with the processing of a broad set of information in their environment independently of current goals [50].

At this point, several studies present electrophysiological differences between groups of children from low and high SES families, but an interesting question is how these differences are distributed among individuals. Using the same *auditory selective attention task*, Isbell et al. [51] found that ERP modulations related to selective attention accounted for individual variability in nonverbal cognitive skills in a group of preschool children from low SES families. Larger frontal and central mean amplitude differences between ERPs to probes, which were embedded in attended versus unattended stories during the selective auditory attention task, were associated with higher nonverbal IQ scores based on multiple regression analysis. These findings extend previous results showing similar links between electrophysiological measures of attentional control system and higher order functions of young children from poor families [69, 71]. Beyond the design limitations to support causal relationships, the importance of these findings resides in the fact that they provide initial evidence about individual relationships between measures according to two levels of organization (i.e., neural activation and cognitive performance).

All the reviewed studies focused on cognitive-related neural activity, and they did not consider neural activity at a lower level of information processing. Sensory neural activity is directly susceptible to exposure to environmental inputs, and these inputs influence higher level processes. Skoe et al. [42] demonstrated neural discrepancies of more basic underlying mechanisms in adolescents with different years of maternal education. They found that the LME level was related to less efficient auditory processing in the brainstem during the passive listening paradigm. In addition, the latter was also associated with a lower performance on working memory and language processes. Specifically, adolescents who had mothers with LME showed less consistency in their response, a weaker encoding of speech, and greater noisier activity in the auditory brainstem responses (ABRs), which reflected lower auditory neural acuity. Furthermore, correlational analyses between the actual years of maternal education and each of the neural measures revealed that the number of years of maternal education was positively associated with a greater consistency of the response, and more robust speech encoding.

Studies on the effects of sensory enrichment, such as musical training and bilingualism, have shown that expertise could be associated with enhanced auditory neural acuity in the brainstem [72, 73]. This implies that improvement in auditory neural acuity could be associated with the level of exposure to specific sound characteristics. Thus, the current state of the nervous system that was provided by the individual's life experience with sound will be reflected in the auditory brainstem response. In turn, it is known that early experiences of the basic sensory system influence the development of higher level functions [74]. In the context of poverty, it has been documented that children from poor families live in backgrounds with lower levels of language exposure, quantitatively and qualitatively, and that these experiences are associated with children's language development [18].

Future research would benefit from a design that allows us to elucidate how brainstem response mediates or accounts for the relationship between poverty-related variables, such as early language exposure and children's receptive and expressive language skills. Because brainstem responses do not require motor or cognitive engagement, these measures could be useful for examining the relationship between lower sensory and cognitive neural networks in children from poor homes. For example, present findings suggest that there may be more basic underlying mechanisms that account for the influence of neural circuitry that subserves attention allocation. That is, an impoverished perceptual representation might be responsible for the degree to which executive attentional network is recruited during cognitive processing.

All these studies pointed out several differences in the neural mechanisms of attention skills and sensory encoding on a variety of tasks. During development, particularly in the first years of life, the nervous system is highly plastic so that important gains in the efficiency of brain functioning may occur because of individual experiences. Thus, an open question that could have a large applied impact is when and how we can implement interventions to take advantage of this neural plasticity to change those initial differences that are related to different developmental contexts. In this sense, only one study evaluated brain activation patterns before and after an intervention (an attentional program training) in lower SES preschoolers [52]. More than 100 children, who were enrolled in a Head Start program, were randomly assigned to the Training Program (TP), Head Start (HS) alone, or to an Active Control Group (ACG). The TP was the only one combining intervention sessions for parents with attention training exercises for children. Although the ACG only performed classroom training for children, the HS group did not receive supplemental activities. The results showed that children who performed the family-based TP had more self-regulatory gains than children who had participated in the other two groups. Specifically, children not only showed higher scores in both nonverbal intelligence and receptive language tasks, but they also showed an increase in the neural response that was reflected in the early attentional modulation (100–200 ms) to attended stimuli, in the spatial auditory attention task (Table 2). In addition, parental reports on children's behavior expressed greater social skills, fewer problematic behaviors, and less parental perceived stress. Finally, the TP group also showed favorable changes in objective laboratory observations of language and interaction patterns. From a neural functioning perspective, these results indicated that the SES disparities in brain activation during development are not necessarily fixed.

The importance of intervention programs resides in the possibility of identifying activities that are able to induce changes in brain development and to determine what aspect of the efficiency of different neural networks could be influenced by different mediating mechanisms. On the one hand, the study by Neville et al. [52] provided important evidence about how activities oriented to parents could improve the brain activity that was related to attentional processes. On the other hand, it did not include direct measures of child and parent stress, or measures of parent-child interactions, such as language exposure or maternal interaction style. Thus, as reasoned by the authors, it is not possible to assess trajectory models that evaluate the mechanism of change, or to establish whether neural attentional changes were mediated by parental changes and/or decreases in child stress regulation.

ERP studies have mainly examined aspects of selective and executive attention, which involve processes of conflict resolution, inhibitory control, and error detection [75]. These processes are associated with a neural network that involves medial frontal cortex, anterior cingulate, lateral prefrontal, and parietal cortices [65, 76]. In addition, ERP evidence indicates associations between poverty and neural processing even when behavioral differences do not emerge [e.g., [41]]. In sum, these studies provide convergent evidence for the association between of poverty on executive and selective attention mechanisms [5, 17, 41, 43, 48–50].

3.4 Frequency Analysis of EEG Baseline Activity and Socioeconomic Status Throughout Development

A number of studies have used frequency analysis of EEG baseline activity to assess how specific power oscillations were associated with different developmental contexts. Brito et al. [46] tested infants at birth using resting-state EEG activity during sleep. They found that frontal and parietal power in gamma bands were associated with memory and language skills at 15 months of age. However, results also showed a nonsignificant correlation between neonatal EEG power and SES variables (i.e., parental education, family income). These null findings suggested that EEG disparities that were associated with SES-related variables, such as education and income, may arise during postnatal experience. Nevertheless, longitudinal designs that include mediation analysis are needed to test whether the EEG differences are explained by different prenatal and postnatal experiences related to poverty.

Baseline brain activity was recorded as early as 6–9-month-olds while viewing video clips [47]. The infants from lower SES homes (measured by gross family income and maternal occupation) showed significantly lower gamma power over frontal regions than those from higher SES homes. Particularly, when infants were compared merely according to gross family income, authors found differences in the power of lower gamma bands (21–30 Hz), whereas differences in high gamma band power (31–45 Hz) were found when groups were compared based on maternal occupation [47]. Based on previous studies [77–80], reduced gamma band activity over frontal areas in infants from low SES backgrounds was interpreted by the authors as a possible early indicator of potential developmental difficulties in attentional control processes and language. Accordingly, differences in resting EEG gamma power correlated with language and cognitive abilities during infancy [46, 79, 81]. For instance, frontal gamma power measured at birth and during the first 3 years of age has been associated positively with individual differences in language and cognitive skills at 1 [46] and 4–5 years of age [81].

In another study, resting-state recordings of adolescents whose mothers had a history of depression manifested greater relative left versus right alpha-band power on alpha band over left mid-frontal scalp areas. This was not predicted by the risk of depression, but rather by SES-related variables such as lower occupation, fewer years of education of the parents, and a smaller probability of being married [56]. These differences were interpreted as indicating a left frontal hypo-activity in lower SES adolescents.

A 6-year prospective study of preschool children made by Otero et al. [53] found differences in EEG power spectra at specific frequencies (Table 1). In the first session, baseline activity of 20–30-month-old infants was recorded while they were sleeping. The findings showed that infants from low SES homes had higher delta and lower alpha power during sleep [55]. The second session was implemented when children were 4 years of age, and in this case, the resting-state activity was recorded in children that were awake and with their eyes closed. The results showed that low SES children had higher power in lower bands (delta and theta) over frontal leads, and lower alpha power, especially over occipital and temporal sites [54]. Interestingly, EEG pattern differences continued during the third session when children were 5 years old. For example, lower SES children showed higher power values in lower bands over frontal areas, but they also showed lower power in alpha band over posterior areas. Finally, although the differences between low and high SES samples diminished with age, these remained at 6 years in frontal theta and occipital-temporal alpha bands [53].

The relevance of these findings resides in the analysis of contextual effects on maturation-related EEG activity changes at different developmental stages. Poverty experienced at 2–6 years of age was associated with different patterns of neural maturation, as assessed by EEG. In addition, the study showed that disparities in neural maturation between groups decreased during the course of development. On the assumption that adverse experiences during the investigated period remained fixed, it could be argued that early disparities were likely to grow during the course of development if these were caused by the accumulation of adversities or stress factors. Otherwise, it could be argued that differences decreased if schooling experience partially counteracted the impact of adverse experiences, which allowed children from poor backgrounds to overcome virtual developmental gaps. Thus, these longitudinal electrophysiological patterns could be partially accounted for by changes in the susceptibility of children to the type of adverse experience during development [82]. Future investigations should focus on how the link between poverty variables and brain signatures is influenced by changes in susceptibility and type of poverty experiences during development.

Another study investigated spontaneous EEG activity patterns in school-age children (6–13 years of age) while having their eyes closed [45]. Consistent with Otero et al. [54], results indicated that children from low SES homes had greater power values than children from high SES backgrounds in delta and theta bands over frontal areas and lower power values in alpha band over temporal and occipital sites. Alpha power was lower, and beta power was greater over frontal areas in low SES children, when compared to the other group. In addition, absolute power decreased with age, whereas relative power increased for higher bands and decreased for lower bands. The authors interpreted these data as showing that children from low SES backgrounds had the EEG characteristics of younger children. In effect, it is known that during infancy and early childhood, there is a decrease in the power of lower frequencies linked to a concomitant increase in the power of higher frequencies [83–86]. Beyond the fact that these spectral trends were found in the studies reviewed here [45, 53], children from poor backgrounds showed a higher prevalence of lower bands that was combined frequently with a lower prevalence of higher frequencies compared to their counterparts at every age [45, 47, 53–55].

Despite the correlational and cross-sectional nature of the great majority of the studies reviewed here, the findings supported the notion of a possible maturational lag, which is in line with MRI findings that show slower rates of brain growth in low SES children between 5 months and 4 years of age [87]. Yet, it is important to note that these findings represent an initial line of evidence, although more longitudinal data are necessary to support that children from poverty context present a maturational lag. In addition, mediation analysis and adjustments for confounding factors are necessary to elucidate how specific poverty experiences explain differences on EEG maturation. Moreover, mediation analysis would help to test whether EEG power differences help to explain the influences of distinct developmental contexts on cognition. These efforts would result in the possibility to use disparities in developmental trajectories of EEG power as cognitive markers that reflect differences in the general cognitive development between children from different SES backgrounds. However, it remains uncertain to which extent these neurophysiological differences are associated with behavioral outcomes. Despite important evidence showing that EEG power and behavior are associated with poverty experience, little is known about how EEG mediates the link between poverty experience and behavioral outcomes in, for example, the acquisition of cognitive skills during infancy.

Taken together, these studies suggest that poverty context may influence a wide frequency range of resting EEG during development. Studies reviewed here showed that children from low SES backgrounds have an increase in the power of low frequencies over anterior sites, and often a decrease in the power of alpha and higher frequencies over the anterior or posterior scalp sites, compared to higher SES samples. These findings that are derived from baseline EEG activity are also consistent with behavioral [28, 67, 88], MRI evidence [37], and ERP studies [5, 17, 41, 48–50]. They suggest that poor environments might exert its influence over brain networks that are related to executive processes, episodic memory, and learning skills.

3.5 Mediation Mechanisms

Almost all EEG studies on socioeconomic disparities lack evidence about mechanisms that could mediate the relationship between childhood poverty experience and brain functioning. Conversely, the literature on the impact of childhood poverty on brain development has proposed two main conceptual hypotheses that could partially explain this link: the *experience of stress* and *early language exposure* [18]. Although the action of these mechanisms is not likely to be independent, specific brain networks would be affected by each of them.

The *experience of stress* in low SES children is likely to be caused by both family and broader environmental characteristics. For instance, children growing up in poverty are more likely to experience bad parenting, family conflict, separation, and to live in chaotic, noisier, crowded, and more dangerous environments [20], all of which can contribute to increase the stress regulation response. Previous evidence suggested the existence of a deregulation of the hypothalamic-pituitary-adrenal (HPA) axis, which usually controls the secretion of cortisol hormone, among others, which contributes to the physiological stress response. Although several studies have agreed on this deregulation hypothesis, some of them have shown a pattern of hypercortisolism [89–92], although others found hypocortisolism [93–95] associated with impoverished backgrounds. The explanations for these discrepancies have focused on participants' characteristics, such as gender, age, and the diversity of adverse experiences [18]. Importantly, at the neurobiological level, a deregulation in stress physiology could have consequences for brain networks with high concentrations of corticosteroid receptors, such as the amygdala, the hippocampus, and the prefrontal cortex (PFC). These areas are sensitive to the effect of stress hormone exposure, and high levels of stress could alter their functioning [18, 90, 96, 97]. On the one hand, the hippocampus and the PFC are involved in the feedback that downregulates the functioning of the HPA axis, while the amygdala plays a facilitating role in the activation of HPA. Sustained exposure of stress hormones, such as cortisol, can produce cellular death, which can damage the functioning and structure of the hippocampus and promote the reactivity of the amygdala. On the other hand, in response to stress, the amygdala evokes the release of high levels of catecholamines and glucocorticoids, which can alter PFC functioning and increases amygdala reactivity [96]. Thus, because higher levels of stress can alter PFC and hippocampal functioning, it increases the functioning of the amygdala that leads to information processing and behavior switches from slow, thoughtful, and “top-down” regulation to a rapid, reflexive, and “bottom-up” regulation.

Previous studies showed that exposure to chronic stressors during childhood mediates the relationship between lower family income in childhood and reduced PFC activity during the regulation of emotions in adulthood [98]. In addition, Blair and colleagues [89] studied a large population that was predominantly low-income, and they found that children who had experienced fewer positive parenting behaviors had higher basal cortisol levels, which was associated with lower performance of executive functions [89]. Inconsistent, unpredictable, and less responsive parenting practices could be stressful for children, because they may feel a lack of control over their physical, social, and emotional needs. In this sense, it was hypothesized that a sustained exposure to stress in unpredictable living environments, and a lower sense of control, could lead children to exhibiting a general “alarm” state [99].

At the neural level, this involves a greater recruitment of networks that are involved in automatic and vigilance processing [18]. These adaptive responses toward a more automatic processing of information could help children to anticipate potentially challenging, negative, or threatening situations. However, it could also have consequences on the self-regulation of behaviors, thoughts, and emotions. Consistent with the *experience of stress* hypothesis of mediation, children with lower maternal education and SES showed comparable frontal activity to relevant and irrelevant information for task goals [5, 17, 49, 50]. Thus, low SES children may be more prone to process the broad set of information available and to have more difficulties inhibiting irrelevant information.

Although the *experience of stress* hypothesis of mediation is gaining more influence on the field of developmental neuroscience [98], it still remains little tested by EEG approaches. D’Angiulli et al. [5] used a direct measure of stress and found that low SES children had marginally higher levels of cortisol than high SES ones. In addition, only the low SES children showed an increase in the electrophysiological response of selective attention, which corresponded to an increase in post-task cortisol levels. Thus, it seems to be the case that low SES children became more stressed by exerting more effortful control to perform the task adequately. In addition, Neville et al. [52] using non-direct stress measure (i.e., self-reports of parenting stress) found a significant large decrease in parenting perceived-stress, after a training program with intervention sessions for parents and attentional exercises for children, relative to either attentional exercises for children alone or normal development of the HS program alone [52].

The *language exposure* hypothesis of mediation is supported by an extensive body of literature that has shown that growing up in low SES backgrounds is associated with poor quantity and quality of language exposure at home. First, it has been shown that parents of children from high SES families read more to their children than parents in low SES families. Second, it has been shown that mothers from low

SES backgrounds use fewer words, less complicated syntax, talk less frequently with their children, and, when they do talk, are more likely to be directing their children's behavior than simply eliciting conversation [100]. Third, the activities that parents choose for interacting with their children are likely to differ according to the SES, and this can influence concrete language-learning opportunities [100, 101]. For instance, some studies have shown that when mothers look for books with their preschool children, they use a more complex and richer speech during this selection process than in other activities [100].

These distinct language-learning experiences across SES were associated in different studies with differences in children's language skills, including vocabulary, phonological awareness, and syntax [36, 100, 102–104]. However, the neural mechanisms through which language exposure may influence child development of language- relevant brain networks are still unclear [101].

Following the *language exposure* hypothesis of mediation, it has been hypothesized that poor language environment could affect brain areas that are related to language processing [105], such as auditory (perisylvian) regions, the visual word form area, and the anterior inferior frontal cortex [101]. Moreover, it has been suggested that both conceptual models, *language exposure* and *experience of stress* hypotheses, are not likely to be completely independent, and they could be supported by overlapping neural mechanisms [82]. On the one hand, stress exposure is likely to interfere with language acquisition. For instance, because a deregulation of stress response could lead to a dysfunction in higher-order cognitive processes, children that are affected by high stress exposure probably have greater difficulty processing complex syntactic structures and concentrating in educational settings [101]. Alternatively, fewer and poorer language-learning experiences could reduce the opportunities to receive rich and complex language stimulation, experiences that help children to develop new skills taxing working memory resources [8, 18].

Up to now, EEG studies have not explored children exposure to language in association with SES disparities. Commonly, composite variables of SES were used to test directly their link with electrophysiological markers or language competencies. For instance, Tomalski et al. [47] found that infants from low SES backgrounds have reduced frontal gamma power, a pattern related to lower language skills in toddlers [79]. In turn, Kishiyama et al. [41] documented that children from low SES families had lower performance on a vocabulary test, but they did not investigate how this was related to the reduced activity found in early EEG components during a visual attention task.

From the perspective of developmental neuroscience, the accumulated evidence suggests that children are specially susceptible to the influence of adverse experiences [59]. For instance, during childhood, there are rapid and important changes in brain functioning, and early exposure to adverse experiences could alter the development more easily and more profoundly than adverse experiences that occur later on. Importantly, specific early alterations can influence the development of other functioning domains later in childhood. Electrophysiological approaches provide a direct measure of that neural functioning and, thus, these techniques are critical for studying how early experience of poverty influences development. Very often, at an early age, differences at the neural level of organization are more evident than differences at the cognitive and behavioral levels [59].

In any case, more research is needed to understand the mediating mechanisms by which the experience of poverty may impact the efficiency of different neural networks during development. Future research should include direct measures of parent and child stress physiology, linguistic environment, and other related poverty experiences that could be used to assess and analyze mechanisms of change. These approaches would help to elucidate the pathways and mechanisms through which distinct experiences of adversities, which are related to poverty, operate at different levels of organization.

4 Future Directions

The exposure to material and sociocultural deprivations is associated with a complex range of influences on neural organization and reorganization at different levels. A key question regarding the influences of poverty on neural and cognitive development is whether these disparities can be overcome by interventions, and what levels of analysis (e.g., molecular, neural, cognitive, behavioral) can support and guide these possible changes. Recent studies indicate that distinct types of interventions were effective in improving the performance levels in cognitive tasks in preschool children who lived in conditions of social vulnerability due to poverty [24, 106–111]. The evidence from the neural level—assessed through EEG—indicates that educational programs promoting parenting skills and cognitive stimulation in children positively influences cognitive performance and neural activity in low SES children. In some cases, these types of gains were achieved in a relatively short time [52]. This preliminary evidence allows both the identification of potential targets and time frames for the design of interventions to generating changes in neural and cognitive development. Furthermore, interventions including EEG measures could help to determine both the underlying mechanisms of gains and the extent of mutability of impacts that are generated by verifiable deprivations in distinct developmental contexts.

Evaluations that consider multiple levels of organization are not applied generally in the context of cognitive interventions beyond the laboratory settings, such as in schools or homes. The inclusion of neural analysis often imposes limitations for use outside the laboratory, because of the added burden of noise, logistics, and transportation. Therefore, it is important to broaden the efforts to extend the design and the implementation of these approaches. Currently, novel methodologies are being developed to improve the signal quality of portable EEG equipment, both in terms of hardware and signal processing, such as artifacts and single-trial analysis techniques [40, 112]. In this regard, efforts that are aimed at transferring laboratory methodologies to different developmental contexts creates the possibility of extending their inclusion to studies with greater ecological value.

In addition, future studies should focus on innovative efforts to include a wider range of EEG paradigms that can be used to test suitable hypotheses about how early adverse experience is related to different patterns of brain development. The findings about effects of poverty or low SES on brain functioning were achieved by using unidimensional measures that could not explain the mechanisms through which poverty impacts brain circuits. Thus, the measures that have been implemented up to now only captured the status of each child indirectly and partially, but they have not considered individual factors that could better characterize the child's experience due to poverty. Conceptual advancements should thus generate new definitions of poverty specifically considering the dynamics of the adversity on children's experiences. This could be achieved by using analyses that have been applied commonly in recent studies of childhood poverty and cognition, such as mixed models [24] or multiple mediation models [8]. These methodological approaches allow the identification of those socio-environmental risks or protective factors that explain the variance of poverty measures on cognitive outcomes [8]. This is especially important because it would provide an ecological and dynamic perspective for each developmental context, which would enable both to capture the effects of specific contextual deprivations on several cognitive systems during development and to fine-tune targets for improvement the design of innovative intervention programs. Thus, future research would benefit from thinking about a definition of poverty in terms of a continuum of effects with several possible outcomes, which depend on the interaction of several crucial factors that are defined by the type, number, and accumulation of risk factors to which children are exposed, the co-occurrence of deprivations, the timing of exposure, and the individual susceptibility to each one. Moreover, electrophysiological approaches would help to elucidate the predictive role of adverse experience on the development of brain functioning. In an interdisciplinary context, electrophysiological approaches would also help to generate information at different interconnected levels of analysis, and they would contribute to building a concept of poverty as a complex phenomenon.

5 Conclusions

ERP studies in relation to poverty have focused mainly on the assessment of attentional mechanisms. The verified associations between poverty and attentional processes might be related to a domain-general effect, which could complement the findings within the social sciences and neuroscience regarding the associations of SES, language, and executive functions. However, resting-state EEG studies have suggested that poverty contexts may influence a wide range of frequencies during development, indicating that a poor environment might influence prefrontal brain areas and their related cognitive processes. Also, some of the studies suggested that there is a maturational lag between children from low and high SES families but, up to now, there are no longitudinal studies that support this hypothesis to demonstrate how these differences evolve through development. Importantly, only one study has explored how these differences change with intervention programs that take advantage of the brain plasticity, especially at young ages. Finally, future studies must benefit from the large conceptual advances that have been made by developmental psychology about the mediators of the influence of poverty on cognitive development, and they should attempt to discern between the two main conceptual theories that have been proposed: *the experience of stress and language exposure*.

The available evidence of influences of childhood poverty on brain functioning supports the notion that improving our understanding about what aspects of deprivations would influence the cognitive development requires (a) the building of an ecological and dynamic approach considering the variability of cognitive outcomes, which depend on the mediating mechanisms associated with the specific adverse experiences that have a dynamic nature and change during development, (b) the design of more elaborate conceptual paradigms to integrate current neuroscientific evidence on indicators of adverse experiences with patterns of brain structure and function, and (c) the assessment of the impact of interventions outside a laboratory setting to incorporate greater ecological measures of children's functioning.

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