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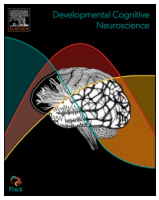

The impact of a monthly unconditional cash transfer on child brain activity: A 4-year follow-up

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ABSTRACT

Early childhood poverty is associated with neurodevelopmental differences, but causal evidence linking income to brain development is sparse. In the present study, we examine whether four years of monthly unconditional cash transfers to mothers experiencing low income cause differences in their preschoolers' brain activity. Shortly after giving birth, mothers were randomized to receive $333/month or $20/month for the first several years of their child's life as a part of the Baby's First Years study. Here we report on the impact of these cash gifts on resting brain electric activity recorded at 4 years of age as measured by electroencephalography (EEG). We find no impact on our primary preregistered outcome (an aggregated index of mid-to-high-frequency brain activity) or our secondary preregistered outcome frontal gamma power. We did find, in additional exploratory analyses that were part of our pre-registered analytic plan, that preschoolers in the high-cash gift group had higher alpha power compared to those in the low-cash gift group. There were no differences in theta, beta, or gamma power between groups. Although the primary and secondary preregistered outcomes showed no group differences our exploratory analyses provide some evidence for impacts on children's alpha power during the preschool years, although this evidence needs further investigation and replication.

1. Introduction

Childhood poverty has long been associated with worse outcomes in adulthood, including lower educational achievement, poorer health, and lower wages and employment(Duncan et al., 1998, 2010; Duncan and Brooks-Gunn, 1997; McLoyd, 1998). It has been argued that one pathway by which these socioeconomic disparities emerge is through environmental, physiological, and family processes, which in turn impact children's brain development(Noble and Giebler, 2020; Troller-Renfree et al., 2022, 2023). This potential mechanism has been supported by studies showing associations between household income and brain structure and function (McDermott et al., 2019; Noble et al., 2015; Sandre et al., 2024; Tomalski et al., 2013; Troller-Renfree et al., 2022). Furthermore, many of the patterns of neural activity associated

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with poverty have also been associated with assessments of language, cognitive, and socioemotional development(Benasich et al., 2008; Brito et al., 2016; Gou et al., 2011; Maguire and Schneider, 2019; Wilkinson et al., 2023). However, nearly all studies showing relations between family income and brain development – and associations between brain development to later cognitive functioning – are correlational, leaving open the question of whether family income *causes* differences in children's brain function.

A growing body of work has found associations between family income across a broad distribution of incomes and differences in children's brain function, as measured by resting electroencephalography (EEG). EEG directly measures the brain's electrical activity while an individual is passively watching a stimulus or opening and closing their eyes, and is thought to reflect important properties of the brain's ability to perform cognitive and social functions. Customarily, resting EEG is characterized by two dimensions: frequency and power.

Frequency (measured in Hz) represents how fast electrical activity in the brain as measured off the scalp is oscillating. It is usually classified into functionally distinct ranges called bands, which are denoted by Greek letters (e.g., delta, theta, alpha, beta, and gamma). Some bands characterize slower or lower-frequency oscillations (e.g., delta, theta), some are mid-range (e.g., alpha), and some bands are comprised of more rapid or higher-frequency oscillations (e.g., beta and gamma). Traditionally, these bands are thought to be functionally distinct, particularly in adulthood, with unique associations with different neurocognitive processes (Cohen, 2017; Siegel et al., 2012; Tan, Troller-Renfree, et al., 2023). For instance, in childhood, resting alpha activity (a middle frequency) has been related to attention and executive function,(Cellier et al., 2021; Kraybill and Bell, 2013) while resting beta and gamma activity (higher frequencies) have been associated with language (Benasich et al., 2008; Brito et al., 2016; Gou et al., 2011), socioemotional functioning (Brito et al., 2019), and higher cognitive skills (Benasich et al., 2008; Brito et al., 2016; Williams et al., 2012).

Power, in contrast, quantifies the amount of energy in a specific band, with higher numbers indicating more energy or activity. Power is commonly described in two ways: absolute power and relative power. Absolute power represents the raw electrical activity in a specific frequency band, while relative power reflects the amount of power in one frequency band expressed as a proportion of the total power across the spectrum.

Resting EEG relative power follows a predictable developmental pattern. As children progress through infancy and early childhood, lower-frequency theta power makes up relatively less of the EEG signal (decreasing relative power), while mid-to-higher-frequency bands increase (increasing relative power) (Cellier et al., 2021; Marshall et al., 2002). This typical developmental tradeoff of lessening relative lower-frequency power and increasing relative mid- to higher-frequency power appears to be altered in children who have experienced early adversity, including lower family income (Tomalski et al., 2013; Troller-Renfree et al., 2020, 2022). As early as one month of age and across early childhood, children in families with lower incomes tend to show lower relative mid- to higher-frequency power in the alpha, beta, and gamma bands compared with their more economically advantaged peers; (Brito et al., 2020; Maguire and Schneider, 2019; Sandre et al., 2024; Tomalski et al., 2013) one study found some evidence for higher power in the lower-frequency theta band (Maguire and Schneider, 2019). Beyond family income, other measures of socioeconomic status (e.g., occupation, education, composite SES measure) and experiences known to be associated with poverty are also correlated with more lower-frequency and less mid-to-higher frequency brain power (Cantiani et al., 2019; Otero et al., 2003; Pierce et al., 2019; Troller-Renfree et al., 2020, 2023). Interestingly, most of the work associating income with brain activity has taken place in infancy, leaving open the question of whether these patterns look similar in later toddlerhood and preschool years. Indeed, at least one study has found that this effect may switch directions later in development (Jensen et al., 2021), and some evidence has suggested that higher gamma may be related to worse outcomes after the infancy period (Nikolaeva et al., 2024; Wilkinson et al., 2019), suggesting that brain signals may serve different functions across the lifespan.

That said, we note three major considerations regarding this body of work. First, many studies report relations between income and brain activity in only one or two frequency bands, and/or only in electrodes over specific brain regions and reports are commonly divided across absolute and relative power. Second, the preponderance of evidence comes from middle-income or affluent families, precluding generalization to more diverse populations. Finally, all of this evidence is correlational and comes from small samples, rendering it impossible to support casual conclusions.

To date, only the Baby's First Years study (BFY; https://www.babysfirstyears.com) has examined whether cash transfers are causally related to child brain activity using a randomized controlled design (Troller-Renfree et al., 2022). Briefly, the BFY study is a randomized controlled trial providing monthly unconditional cash transfers, hereafter referred to as "cash gifts," to mothers who gave birth while residing in households with incomes at or below the federal poverty line in four metropolitan areas of the United States. One thousand low-income mothers were randomized at the time of their child's birth to receive either a large cash gift of $333 per month (termed the "high-cash gift group") or a nominal cash gift of $20 per month (the "low-cash gift group;" for more information on study design see Noble et al., 2021) for the first several years of their children's lives. The high-cash gift represents approximately an 18 % increase in average baseline household income, and over the first three years we observed BFY high-cash gift households reporting a 14 % increase in net income (including the cash gift)(Noble et al., 2024). Considerable evidence suggests that increased family income is likely to impact the development of children residing in economically disadvantaged environments, with two main theorized pathways being increased parental investment in children and decreased material hardship and related parental psychological distress (Becker, 1992; Evans, 2004; Mistry et al., 2002).To date, evidence from BFY has supported the increased investment pathway (Gennetian et al., 2024), but not the material hardship and parental distress pathway(Magnuson et al., 2022).

Based on the observed associations between socioeconomic factors and brain activity in the literature at the time of the study's original preregistration (in 2018), we hypothesized that, after the first year of cash gifts, the infants of the mothers in the high-cash gift group would show reduced theta power and increased alpha and gamma power, compared with the infants of the mothers in the low-cash gift group. Based on research that subsequently emerged (Brito et al., 2020), we also examined beta power, with a similar hypothesis that we would see increased beta power in the high-cash gift group relative to the low-cash gift group. Although the majority of impacts investigated across frequency bands and types of power were not statistically significant after one year of cash gifts, we found suggestive evidence that the cash gifts were associated with higher beta power (absolute power: effect size = .26, p = .02; relative power: effect size = .19, p = .09), higher gamma power (absolute power: effect size = .23, p = .04; relative power: effect size = .16, p = .18), and marginally higher alpha power (absolute power: effect size = .17; p = .07; relative power: effect size = .16, p = .17), consistent with our expectations that the high-cash gift group would show more power in these bands(Troller-Renfree et al., 2022). However, none of these preregistered analyses reached conventional significance after correction for multiple comparisons. Complicating our interpretation further, the age-1 EEG sample was limited to those families who we were able to assess in-person prior to the onset of the Covid-19 pandemic (N = 435).

In the present paper, we present estimates of impacts on children's brain activity after four years of a planned six years of monthly unconditional cash transfers. To date, studies of the associations between family income and brain activity have been concentrated in infancy and

toddlerhood, with less research attention focused on the preschool period, despite the preschool years continuing to be a sensitive period for many areas of brain development(Luby et al., 2020). We preregistered the analytic plan and hypotheses for primary and secondary analyses on clinicaltrials.gov (ClinicalTrials.gov Identifier: NCT03593356).

Here, after summarizing the results involving the primary preregistered index, we present secondary analyses examining the theta, alpha, beta, and gamma frequency bands,[1] using a conventional neuroscientific approach to analyzing resting EEG data (See Table 1 for sample characteristics). Because all three mid- to high-frequency bands were components of the preregistered composite index, we did not preregister these as primary or secondary outcomes. However, the analysis plan that accompanied our preregistration stated that we had uniform directional hypotheses for these bands (hypothesizing more power in the high-cash gift group), that we would estimate MLM models in each band, and that, in each case, we expected group differences, such that the high-cash gift group would show more whole-brain power in each band. These models include main effects of group and region (frontal, temporal, central, parietal, occipital), as well as a group x region interaction, for each frequency band. Additionally, because of past research correlating income with frontal gamma power (Brito et al., 2020; Otero et al., 2003; Tomalski et al., 2013) and frontal gamma power with subsequent cognitive and language skills, (Benasich et al., 2008; Brito et al., 2016; Gou et al., 2011; Williams et al., 2012) as well as our finding of group differences in frontal gamma power after the first year of cash gifts, we pre-registered one secondary regional hypothesis – of higher frontal gamma power among children in the high-cash gift group relative to the low-cash gift group. Consistent with our approach at Age 1 and with field suggestions to report both (Troller-Renfree et al., 2024), we report both absolute and relative power and our hypotheses were consistent across these power computations. All other group-by-region interactions were considered exploratory.

Table 1
Sample Characteristics for High-Cash and Low-Cash Gift Groups in the Age-4 EEG Analytic Sample (N = 637; See Table SI1.2 for complete list of baseline measures).

	Low-cash Gift		High-cash Gift		
	Mean (sd)	N	Mean (sd)	N	p-value
Child is female	50.1 %	359	50.4 %	278	0.915
Child age at visit (years)	4.0 (0.18)	359	4.0 (0.14)	278	0.275
Mother education (years)	11.9 (2.93)	354	11.8 (2.9)	276	0.752
Mother race/ethnicity: white, non-Hispanic		359		278	
White, non-Hispanic	9.2 %		7.6 %		0.319
Black, non-Hispanic	38.7 %		42.5 %		0.206
Hispanic	43.4 %		46.0 %		0.355
Multiple, non-Hispanic	3.6 %		2.5 %		0.368
Other or unknown	5.0 %	359	1.4 %	278	0.005
Household combined income at baseline	$22,237 (18,910)	338	$22,055 (16,827)	254	0.879
Number of artifact-free epochs	230.0 (92.5)	359	230.9 (92.9)	278	0.898

Notes: Data are presented as means or percentages with standard deviations in parentheses. Child age at visit and number of artifact-free epochs were measured at the Age-4 visit. All other characteristics, including household income, were measured by maternal report at baseline prior to random assignment. Household income includes income from all members of the household. Reported p-values of mean differences are unadjusted. As reported in SI1.2, joint tests of equality of means across all baseline characteristics for the EEG sample were not significant. See Table SI1.2 for full baseline balance assessment.

[1] The delta band was not examined as it was not pre-registered, has not been reliably associated with income, and our 1-second epochs do not allow for the reliable resolution of delta activity.

2. Methods

2.1. Participants

Participants comprised one thousand mother/infant dyads enrolled in the Baby's First Years study (for more details see (Noble et al., 2021)). Mothers were recruited in hospital postpartum wards in four United States metropolitan areas: New York City, New Orleans, Omaha and the Twin Cities (Minneapolis and St. Paul). Upon enrollment into the study, 40 % of the mothers were randomly assigned to receive a large monthly cash gift of $333 per month (high-cash gift group) and the remaining 60 % received a nominal monthly cash gift of $20 per month (low-cash gift group; see Supplement 1 for inclusion and consort diagram). Cash gifts began at the hospital and were originally intended to continue until children were 40 months of age. However, cash gifts were subsequently extended twice – once to 52 months and then to 72 months. Random assignment was a continuous process over the enrollment period. Prior to launching the study, we secured approvals from state or local officials to ensure that, to the extent possible, participants would not lose eligibility for most public benefits due to the cash gift. The Institutional Review Boards of Teachers College, Columbia University; the University of California, Irvine; and the New York State Psychiatric Institute approved this study. Participants provided informed consent for all study activities. For more information about the Baby's First Years Study see https://www.babysfirstyears.com, Noble et al., 2021, and the Interuniversity Consortium for Political and Social Research (ICPSR) data repository (Magnuson et al., 2020).

Mothers and infants were from racially and ethnically diverse backgrounds, with the majority of mothers identifying as Black or Hispanic (see methods for more information). By design, no infants required intensive care at birth, and virtually all were of normal birthweight and gestational age (see Table 1 for sample characteristics of the EEG subsample and Supplement 1 for a CONSORT diagram and information on baseline balance).

The present paper reports on resting functional brain activity obtained during the Age-4 wave of data collection (mean = 4.03 years, SD = 0.19). For age-4 data collection, 984 of the original 1000 mother-infant pairs remained eligible (there were five maternal deaths, five child deaths, two maternal-child separations, and four instances of maternal incarceration). To incentivize in-person participation, participants were offered financial research incentives, a free meal, sibling child care, and prepaid transportation to the university research site. In total, 892 of the original 1000 participants provided at least some data at the age-4 wave (95 % of the high-cash gift group and 88 % of the low-cash gift group). A total of 824 participants completed an in-person visit at which the target child was present. Of those 824 families, 754 provided consent for EEG-related data collection (92 %). Of the families who consented to EEG data collection, a total of 637 ultimately provided usable EEG data (84 %); see Supplement 1 for CONSORT diagram; see Supplement 4 for nonresponse adjustments using Toolkit for Weighting and Analysis of Nonequivalent Groups (TWANG) (Ridgeway et al., 2022).

2.2. Data collection

To assess brain activity, EEG data were collected using four lab-based EEG systems provided by Magstim EGI, Eugene, OR. All EEG data were recorded using a 128-channel Geodesic Sensor Net (Magstim EGI, Eugene, OR) with eye and face electrodes removed. As our sample is both racially and ethnically diverse, modified geodesic sensor nets with longer pedestals were made available, and specialized net application protocols were used to increase inclusivity in our recordings (see Adams et al., 2024; Troller-Renfree et al., 2021 for more information). Following cap application, impedances were kept below 50 kΩ

whenever possible. The sampling rate was 1000 Hz and data were referenced online to Cz. During the recording, children sat on a chair approximately 60 cm from the monitor while they watched silent non-social videos of toys currently being used as a part of data collection for the Healthy Brains and Child Development Study (HBCD, see (Fox et al., 2024) for more information). Recordings lasted approximately 3 min. Following the resting task, participants also completed an auditory oddball task, which will be presented elsewhere (see Sandre et al., *in prep*). Data were analyzed offline on virtual machines without any group information available to data processors.

2.3. EEG processing

EEG preprocessing was conducted with EEGlab (Delorme and Makeig, 2004), custom MATLAB scripts (MathWorks, Natick, MA), and the MADE processing pipeline(Debnath, Buzzell, et al., 2020). First, as the MADE pipeline utilizes independent components analysis (ICA) for systematic artifact removal, all EEG data from resting and task-related recordings were visually inspected, and any non-brain data (e.g., recording after cap removal) were removed. Next, resting and task-related data were merged together to maximize data for ICA. Then, the bottom row of electrodes was deleted from merged, continuous EEG data and was high-pass filtered at 0.3 Hz and low-pass filtered at 50 Hz. The EEGLAB plug-in FASTER(Nolan et al., 2010) was used to identify bad channels prior to using the standard MADE ICA removal procedure. Artifactual ICs were removed from the original dataset using the Adjusted-ADJUST algorithm(Leach et al., 2020).

Following ICA, resting EEG data were separated from the task-related EEG data and segmented into 1 s epochs, which were allowed to overlap by 50 %. Following the segmentation procedure, residual ocular artifacts were removed by completely rejecting any epochs in which the ocular channels' (electrodes 1, 8, 14, 21, 25, and 32) voltages exceeded ±100 μV. Next, bad channels were identified by examining if channel voltages exceeded ±100 μV. Channels containing artifact were interpolated(Perrin et al., 1989) at the epoch level. However, if more than 10 % of the channels (not considering globally rejected channels) were interpolated, the entire epoch was removed from further processing.

Fast Fourier Transform (FFT) with a hanning window was used to deconstruct

the EEG data into frequency bands. Spectral power (μV^2) was averaged into four

frequency bands outlined in our preregistered analytic plan: theta (3–6 Hz), alpha (7–12 Hz), beta (13–20 Hz), and gamma (21–45 Hz). Delta power was not examined as it could not be resolved reliably given the short epoch length (1 s), which was selected in order to retain as many participants as possible. Relative power was calculated for each frequency band by dividing the amount of absolute power in a given band by the total amount of absolute power across all of the frequency bands. All multi-level models use regional power. To compute regional power, electrodes were grouped into frontal, central, parietal, temporal, and occipital regions. Electrodes were grouped as follows: frontal (20, 12, 5, 118, 24, 19, 11, 4, 124, 27, 23,18, 16, 10, 3, 123), central (6, 112, 105, 87, 79, 54, 37, 30, 13, 106, 80, 55, 31, 7, Cz), parietal (53, 61, 62, 78, 86, 52, 60, 67, 72, 77, 85, 92), temporal (40, 46, 39, 45, 50,109, 102, 115, 108, 101), and occipital (66, 71, 76, 84, 70, 75, 83).

2.4. Statistical analysis

Analysis was guided by BFY's preregistered data collection and analysis plan (ClinicalTrials.gov Identifier: NCT03593356). As such, group differences were estimated separately for each band of absolute and relative power following the ANOVA framework. Specifically, we estimated multi-level models using restricted maximum likelihood estimation (REML) (a repeated measures mixed model) with cash gift group as the between-subjects factor and region as a within-subjects factor. We use the XTMIXED command in Stata, nesting individual child within cash gift group; in this approach, an error term is not specified, reducing likelihood of incorrect specification. Stata estimates an error term for the between-subject effects nesting individual in group, and the error term for the within-subject factor (brain region with five categories: frontal, central, temporal, parietal, occipital) is the residual error for the model. To attenuate any potential bias from outliers, measures were truncated at the 99th percentile, which is consistent with the approach used in other Baby's First Years reports(Magnuson et al., 2022). Models included all pre-registered covariates, accounting for baseline child and family demographics, and the number of artifact-free epochs. We had no missing data among our primary measures and very little missing data (<1 %) for our covariates; for missing data among covariates, we include a missing data indicator and impute the mean value among the whole sample. Individual frequency bands were not preregistered as formal secondary outcomes because they were a component of our preregistered aggregated composite index. Multiple comparison adjustment across bands were not preregistered, as the MLM models were meant to follow up our primary outcome and frequency bands are thought to be functionally distinct and thus, correction across bands is not common practice. For robustness, ITT differences were also estimated using an Ordinary Least Squares (OLS) regression. In this model, an indicator for assignment to the high-cash gift group and all pre-registered covariates were regressed on the outcomes. We provide corrections for multiple comparisons among these OLS models to be consistent with our prior work(Troller-Renfree et al., 2022).

3. Results

3.1. Primary preregistered index measure of alpha, beta, and gamma power and secondary preregistered frontal gamma analyses

All primary child behavioral outcomes, as well as a composite index measure of EEG created using a data reduction technique commonly used in economics and other social science fields (but not neuroscience), are reported elsewhere(Noble et al., 2024). Briefly, the primary pre-registered index of whole-brain activity sums power between 7 and 45 Hz (alpha, beta, and gamma bands). As shown in Table SI3.2, children in the high-cash gift group had a somewhat higher value on this index than children in the low-cash gift group (effect size = .12), but this difference did not reach statistical significance (effect size = .12, $p = .11$). Similar results were obtained from models estimated with a series of robustness checks, including robust regression techniques, multiple imputation, and weighting-based nonresponse adjustments (Noble et al., 2024).

For the **gamma band**, our preregistered secondary outcome was about gamma power in a single (frontal) region. In a Muli-level model analysis main effect of group and group-by-region interactions did not reach statistical significance, suggesting that group differences in gamma power were neither stronger nor weaker over any specific region. Using a regression-based intent-to-treat analysis, we found that group differences in frontal gamma were not statistically significant (Effect size = -.09; $p = .266$; see Table SI3.2).

3.1.1. Multi-level model analyses

As described in our preregistration analytic plan, and consistent with the methods used by another prominent RCT (Debnath, Tang, et al., 2020; Marshall et al., 2004), we present 8 exploratory multi-level models estimating group differences in absolute and relative brain power across four frequency bands (theta, alpha, beta, and gamma). Each model includes five brain regions. For each frequency band, we estimated the main effect of cash-gift group assignment (high vs. low) and a group-by-brain-region interaction (regions: frontal, temporal, central, parietal, occipital). To do this, we approximated an ANOVA by estimating a multi-level model using the restricted maximum likelihood (REML) approach. Results are summarized in Table 2.

Table 2
Descriptive Statistics and Multi-Level Model-based Cash Gift Treatment Estimates from Preregistered Analyses Examining Group Differences in Brain Power.

	Low Cash Gift Group Mean	High Cash Gift Group Mean	Main effect of treatment with site fixed effects and covariates	Effect Size	Treatment Main Effect p-value $p < Chi^2$	Chi2	Treatment X Region P-value $P < Chi^2$	Joint Chi^2
Absolute Alpha	2.051	2.203	0.163 + (0.089)	0.16	0.067	3.35	0.209	7.16
Absolute Beta	0.518	0.523	-0.004 (0.016)	-0.02	0.811	0.06	0.220	7.00
Absolute Gamma	0.319	0.314	-0.013 (0.013)	-0.07	0.308	1.04	0.376	5.34
Absolute Theta	5.558	5.640	0.128 (0.188)	0.06	0.498	0.46	0.825	2.17
Relative Alpha	0.239	0.249	0.009* (0.005)	0.15	0.050	3.85	0.173	7.70
Relative Beta	0.063	0.063	-0.001 (0.001)	-0.06	0.398	0.71	0.360	5.48
Rel. Gamma	0.039	0.038	-0.002 (0.001)	-0.08	0.194	1.69	0.363	5.46
Relative Theta	0.658	0.650	-0.007 (0.005)	-0.10	0.217	1.52	0.459	4.66

Notes: Standard deviations (columns 2 and 3) and standard errors (column 4) in parentheses. + $p < 0.10$; * $p < 0.05$; ** $p < 0.01$. Not the p-value for relative alpha rounds to 0.050 from a p-value below the threshold of.05.
Estimates are from a multilevel model estimated in Stata using restricted maximum likelihood (REML), approximating a repeated measures ANOVA. Effect size estimates for main effect of treatment (column 5) use the low-cash group standard deviation as denominator. All band measures truncated at the 99th percentile. P-values reported use the Chi2 statistic Covariates include maternal self-report covariates from the BFY baseline survey conducted at the time of enrollment: mother's age, completed maternal schooling, household income, net worth, general maternal health, maternal mental health, maternal race and ethnicity, marital status, number of adults in the household, number of other children born to the mother, maternal smoking during pregnancy, maternal alcohol consumption during pregnancy, father living with the mother, child's sex, child's birth weight, and child's gestational age at birth. Models also control for measures drawn from the age-4 visit, including child's age in months at the time of the EEG assessment, and the final number of usable epochs. Models also include site fixed-effects reflecting the site of random assignment.

For the **theta band**, we observed no significant main effects or group-by-region interactions for absolute or relative power.

For the **alpha band**, a main effect of group for relative alpha reached statistical significance (*Effect size* = .15; $p < .050$). The main effect of group for absolute alpha was not significant (*Effect size* = .16; $p = .067$). Group-by-region interactions were not statistically significant, suggesting that group effects were not meaningfully different in magnitude across brain regions.

For the **beta band**, no main effect of group or group-by-region interactions reached statistical significance for absolute or relative power.

3.1.2. *Exploratory analyses, reliability, and robustness checks*

To further interrogate the group differences observed in the alpha band, we conducted several exploratory analyses, reliability checks, and robustness checks.

3.1.2.1. OLS-estimates of group differences. Consistent with the analytic approach from previous reports of brain activity from the Baby's First Years project, we conducted analyses using the regression-based approach reported in Troller-Renfree et al., (2022) (Supplement 3). In these analyses, both absolute and relative alpha power reached conventional statistical significance before, but not after, corrections for multiple outcomes, when all bands are considered as a family. No group differences in power in any of the other bands were detected.

3.1.2.2. Weighted analyses to adjust for non-response. As is common in pediatric EEG research, we failed to obtain usable EEG data for a substantial subset (35 %) of the larger study sample owing to non-consent, child fussiness and other reasons (see CONSORT diagram for more information). Valid resting EEG data were obtained from 70 % of the high-cash gift group and 61 % of the low-cash gift group. This difference of ~9 %age points is not specific to EEG and is already present between groups when examining whether an in-lab visit with a child took place (high-cash = 89 %; low-cash = 79 %), perhaps suggesting that high-cash gift moms feel more motivated to participate or able to get their family into the lab. This raises questions about systematic differences between children who did and did not provide valid data, which could lead to biased inferences about impacts in the larger study sample.

In order to investigate possible biases in the intent-to-treat estimates, we used the Toolkit for Weighting and Analysis of Nonequivalent Groups (TWANG)(Ridgeway et al., 2017) to generate weights that minimized differences in baseline characteristics between the sample at random assignment and the sample with valid EEG data at 4 years of age. These analyses showed that the observed, unweighted effects in absolute and relative alpha were broadly similar to weighted adjustments (Supplement 4). We also generated weights that minimize difference between the age-4 high-cash and low-cash gift groups on baseline characteristics. These findings suggest that group differences in beta and gamma may be sensitive to some of the observed imbalance between the high-cash and low-cash gift groups, with a slight increase in the magnitude of effect sizes (see Supplement 4 for further discussion).

3.1.2.3. Impacts on frontal gamma power. We investigated the robustness of the pre-registered secondary outcome, frontal gamma, results using robust regression techniques and TWANG-based nonresponse corrections (see Supplement 2). In all cases, group differences were small and statistically nonsignificant, and thus, we conclude there is no evidence of group differences in frontal gamma.

3.1.2.4. Associations between EEG power and child cognition and behavior. Because of past work showing associations between EEG power and cognition and behavior (Benasich et al., 2008; Brito et al., 2016, 2019; Cellier et al., 2021; Gou et al., 2011; Kraybill and Bell, 2013), we examined in exploratory analyses concurrent correlations between EEG power and child behavior. Overall, the correlations between brain and behavior were small (never exceeding an absolute value of.11) these analyses showed small correlations between beta and gamma power and parent and experimenter-rated behavior problems, suggesting higher beta and gamma power was associated with parent report of worse behavior problems and attention/impulse control as rated by a research assistant. As well, there were small correlations between alpha power and attention/impulse control suggesting that higher alpha power was associated with better attention/impulse control as rated by a research assistant and fewer parent-reported behavior problems (Supplement 5).

3.1.2.5. Reliability of EEG power. Using Spearman–Brown split-half correlation method, we confirmed that our estimate of EEG power is reliable and stable (Supplement 6)(Troller-Renfree et al., 2021).

3.1.2.6. Potential artifact in the temporal region. Based on our topographic heat maps (Fig. 1), we identified some potential motion artifact in the temporal region. As such, we interrogated our processing parameters and the distribution of power values and found no source of major concern. Nonetheless, we reanalyzed our reported impacts while excluding the temporal region (Supplement 7). We found that effect sizes changed minimally (.00–.03), even in the beta and gamma bands. However, the effect size of our primary preregistered outcome increased in size slightly, perhaps suggesting that the temporal artifact may have added additional noise to whole-brain estimates that may have obscured group differences in higher-frequency power (.02 increase, *effect size* = .14, p = .084) and the high sensitivity of findings to analytic decisions.

3.1.2.7. Regional differences in alpha power. Finally, although there were no significant group by region interactions in alpha power, we describe regional group means, effect sizes, and p-values for alpha in Supplement 8.

4. Discussion

Researchers have long debated whether family income itself impacts children's brain development, or whether differences in brain development associated with family income should be attributed to many of the other factors confounded with the experience of lower economic resources(Noble and Giebler, 2020; Troller-Renfree et al., 2022). The Baby's First Years study was designed to identify the causal impact of monthly unconditional cash transfers to families with low income beginning shortly after the birth of their children on family life, children's development, and brain activity. As we show in Table SI3.2 and report in detail elsewhere (Noble et al., 2024), we found no evidence of impacts on our primary preregistered child brain activity outcome, a composite index of children's mid-to-high-frequency brain activity. And, as we show in tables SI2.1-SI2.3 and discuss elsewhere(Noble et al., 2024), we found no evidence of impacts on our secondary preregistered outcome of frontal gamma.

Here, we highlight the results of additional exploratory analyses, using the prevailing analytic approach among other studies examining adversity-reducing interventions and policies(Brito et al., 2022; Marshall et al., 2008). These analyses better contextualize our primary preregistered composite index of brain activity, by focusing on the

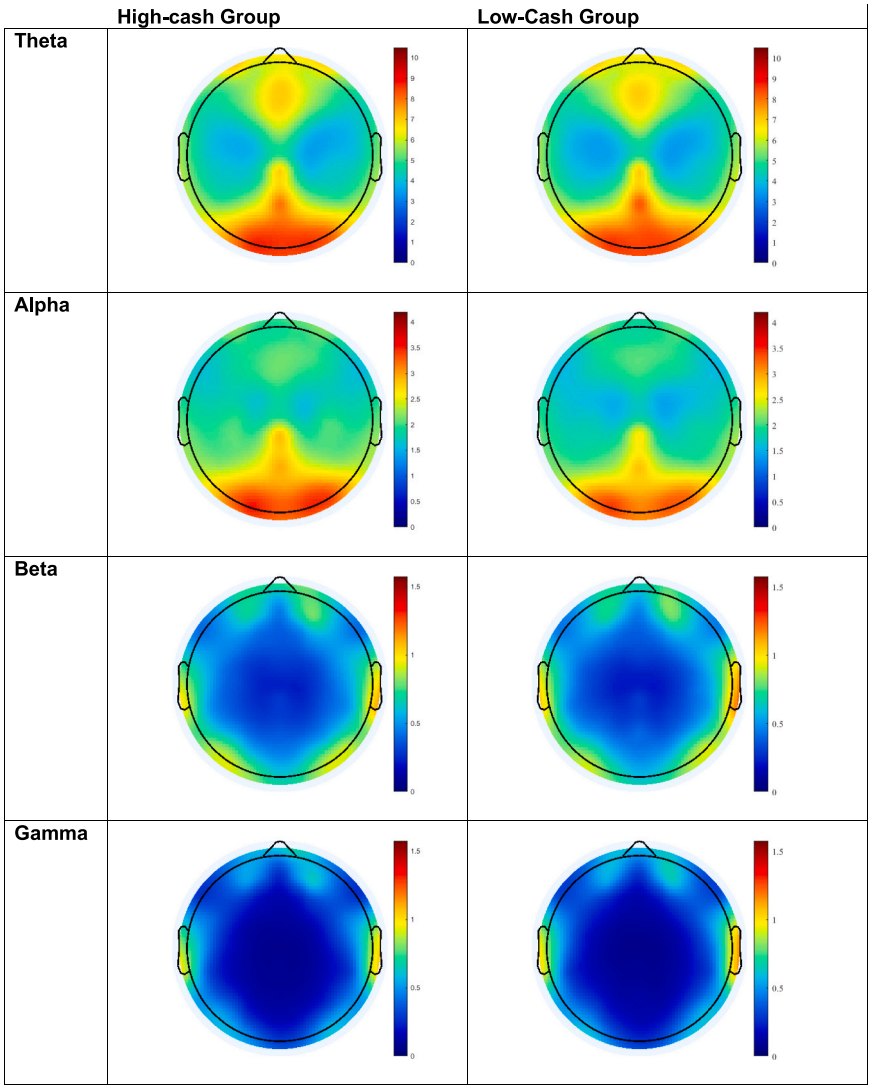

Fig. 1. False color topographic heat maps. Topographic heat maps showing the distribution of absolute theta-, alpha-, beta-, and gamma-power across the scalp for the high-cash gift group (Left) and low-cash gift group (Right). Warmer colors represent more power, while cooler colors represent less power. Heat maps also illustrate the presence or absence of any major artifact (e.g., eye blinks or movements).

underlying frequency bands – alpha, beta, and gamma –and as we described in our pre-registration analytic plan using multi-level models, found greater relative alpha power in children in the high-cash gift group relative to children in the low-cash gift group, with an effect size of.15 ($p < .050$), but not significant for absolute alpha. Impacts on absolute and relative alpha at Age 4 are similar in effect size to the non-significant difference observed in absolute alpha when children were approximately 12 months of age (see Fig. 2).

Previously, after the first year of cash support for the subsample of infants tested prior to the onset of the pandemic, we observed the largest positive impacts on beta and gamma power, driven primarily by differences in the frontal and central regions (Troller-Renfree et al., 2022).

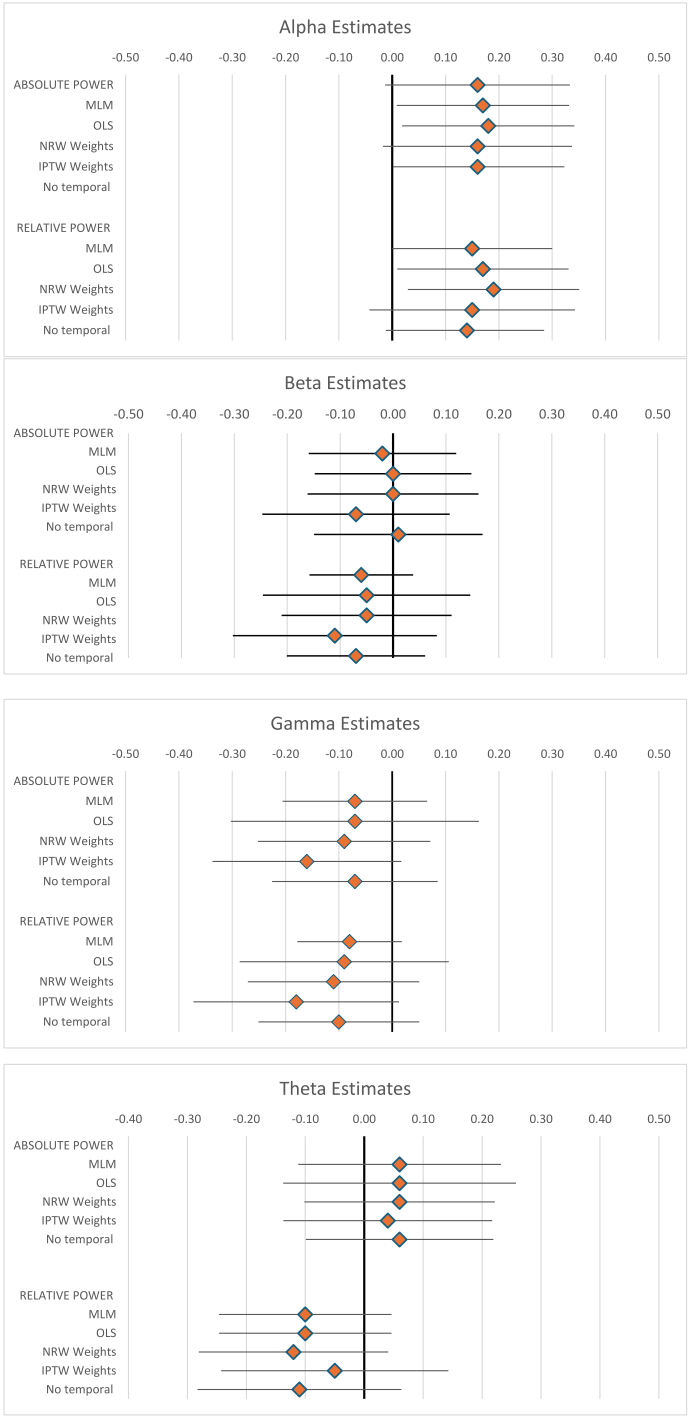

Fig. 2. Forest plot of all EEG band effect sizes and 95 % confidence intervals across age and estimation techniques. All estimates are at Age 4 unless otherwise noted. Forest plots detailing effect sizes of all band estimates with 95 % confidence intervals. Effect sizes for absolute power values grouped on the top and relative power are on the bottom. Methods for estimates are: "MLM" – multilevel model, "OLS" is our standard impact shell, "NRW Weights" the non-response weights applied to the OLS model from Supplement 4, "IPTW Weights" the inverse probability of treatment weights applied to the OLS model from Supplement 4, and "No temporal" is the whole-brain estimate without the temporal electrodes from Supplement 7. Note that the opposite directions of absolute and relative theta is not due to noise in the estimates and rather that absolute and relative theta are commonly negatively associated flipping of this association can be attributed to the way in which relative power is calculated, which is a proportion (see Troller-Renfree et al., 2025 for further discussion).

Yet, after four years of monthly cash transfers, we observed no significant impacts on preschoolers' beta or gamma power, although we did see evidence for significantly less beta and gamma power in the high-cash gift group in some of our weighted models, which is contrary to our hypotheses (Fig. 2). We also found no impacts for frontal gamma specifically, which we hypothesized would be higher in the high-cash gift group relative to the low-cash gift group.

We know very little about the specific aspects of poverty that shape beta and gamma power in toddlerhood, making it difficult to pinpoint whether the patterns we observed at 12 months of age would be expected to persist in later development. Nevertheless, there are several reasons we see a different patten of impacts on beta and gamma power between infancy and during the preschool years. First, it is likely that young children have more varied and wider experiences than infants, and it may be the case that cash transfers are less likely to affect the quality of these environments (e.g., childcare or preschool), reducing the overall impact of cash transfers on brain activity. Second, while we have seen consistent evidence that the cash gifts increase families' investments in children (Gennetian et al., 2024), we see no impacts on maternal psychological distress. Moreover, while net family income has increased over the course of the study, the majority of BFY families continue to reside in households with income less than twice the federal poverty line (Magnuson et al., 2022). Thus, the cash gifts may not have been large enough to change family environments in ways that would meaningfully affect brain activity at 4 years of age. Third, it is possible that the pathways by which cash transfers might affect families and children were changed by the COVID-19 pandemic (for a thorough discussion of how pandemic-related experiences may have affected families, see Noble et al., 2024)). Fourth, to date, most of the observed associations between income and higher-frequency power have been measured during infancy (Brito et al., 2020, p. 202, 2022; Sandre et al., 2024; Tomalski et al., 2013), but recent evidence suggests that associations between material resources and beta and gamma power may reverse in toddlerhood (Jensen et al., 2021), and that higher beta and gamma may be associated with worse outcomes during the preschool years (Nikolaeva et al., 2024; Wilkinson et al., 2019) (Supplement 5). Fifth, it is possible that estimates are sensitive to methodological differences that varied across data collection waves, including location of data collection (home vs. lab), EEG system (portable vs. lab-based), electrode number and type (20 dry electrodes vs. 100 + saline electrodes), and/or task type (a colorful video with sound vs. a soundless video of slow-moving toys). It is also possible that artifactual differences observed at age-4 obscured group differences (Supplement 7). Finally, it is possible that our findings after the first year of cash gifts were spurious, and we are seeing expected regression to the mean.

For alpha power, we found somewhat consistent differences between the two cash gifts groups (effect sizes.14–.16) among both infants and preschoolers (see Fig. 2), despite modest correlations across time (r = .17–.22). These impacts were statistically significant at 4 years of age in relative alpha power, and similar in magnitude but not significant in absolute alpha power. The consistency in effect size across time may point to a small impact, but the lack of significance in many of these analyses highlights the need further investigation and replication. If confirmed through future preregistered analyses and replication, Alpha power could provide a useful target for intervention research. In some ways, alpha is an ideal target, as it is the most easily identifiable band across the lifespan due its highly visible and characteristic peak in the power spectrum. Also, newer computational methods allow for oscillatory alpha to be easily separated from background brain activity (Donoghue et al., 2020; McSweeney et al., 2023). Indeed, a recent methodological paper shows that experts in pediatric EEG were much more consistent in their definition of the alpha band than the beta and gamma bands, again highlighting its potential for replicability (Troller-Renfree et al., 2024).

Impacts on alpha power are among the most consistent findings in the adversity-reduction literature, with both paid family leave and foster-care interventions being associated with greater alpha power across during infancy, childhood, and adolescence (Brito et al., 2022; Vanderwert et al., 2010). Correlational work suggests that alpha power is sensitive to early environmental experiences like maternal stress (Troller-Renfree et al., 2020, 2023), socioeconomic status(Maguire and Schneider, 2019; Otero et al., 2003), and psychosocial deprivation(Bick et al., 2022; Debnath, Tang, et al., 2020; Marshall et al., 2004; Sheridan et al., 2012; Tan, Tang, et al., 2023; Vanderwert et al., 2010). While alpha power may be sensitive to early experiences of adversity, as well as to interventions and policies that improve children's circumstances, it is not clear which aspects of these early experiences may be the key factors affecting alpha power.

Turning from predictors of alpha to associations between alpha and neurocognitive behaviors, it is important to remember that EEG is an indirect measure of behavior and should not be used as direct evidence of enhanced cognition. Indeed, past work is not sufficient to indicate how an effect size of ~.16 in alpha power might translate to neurocognitive functioning. In our own data, we see some evidence suggesting that higher resting alpha power may be weakly associated with better attention/impulse control as rated by a research assistant and fewer behavior problems as rated by their mother (see Supplement 5), but we do not see group differences in these measured outcomes at age 4. Indeed, given the weak correlation between alpha power and attention, we would need a very large impact on alpha power to see any significant differences in our measure of attention. Alternatively, it may signal the possibility that differences in direct assessments of neurocognitive and mental health outcomes will emerge later (sometimes called "sleeper effects"), or that we are not measuring the types of behaviors that alpha power most strongly supports.

The study has some important limitations. First, as with most EEG studies, we were only able to collect valid EEG data for a subsample of the participating children. This decreases statistical power and introduces opportunities for biases in our estimates. For instance, we had a gap among children who contributed usable EEG data, with 61 % of the children in the low-cash gift group versus 70 % of the children in the high-cash gift group. Although we conducted sensitivity analyses using weights to correct for any baseline differences in these samples, the possibility of differential attrition biasing our results remains. Second, a field-level limitation is that much is still unknown concerning the stability and predictive value of early brain signals. As such, we encourage researchers to use caution in the interpretation of the present findings, particularly in considering certain patterns as being "better" or "worse" patterns of brain activity. Third, as we see in Fig. 1, we observe a small but visible amount of possible artifact in the beta and gamma bands in the temporal regions surrounding the ears (see Supplement 7 for further discussion and robustness check). While we cannot be sure of the cause of this potential artifact, it is possible that our beta and gamma estimates across the entire head may be contaminated by some level of non-brain artifact due to volume conduction. This artifact could obscure or warp any possible treatment effects and, as such, our estimates should be treated cautiously.

Taken together, the EEG results indicate that providing four years of monthly unconditional cash transfers to families who were living in poverty at the time of their child's birth did not produce differences in our primary or secondary preregistered brain outcomes. Exploratory analyses that were part of our pre-registration analytic plan reveal a possible causal impact on a select aspect of preschoolers' brain activity – namely, mid-frequency alpha power, but not low-frequency theta, or higher-frequency beta or gamma power. This may suggest that unconditional cash transfers may impact brain activity differently across development, from infancy through the preschool years, but more work is needed. Because whole-brain alpha power was not a preregistered outcome, the impact of unconditional cash transfers on brain activity in this frequency band needs further study and replication. As such, associations between cash transfers and alpha power are a promising avenue for future research on how income might affect brain activity in the

preschool years.

CRediT authorship contribution statement

Katherine Magnuson: Writing – review & editing, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Lisa A. Gennetian:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Hirokazu Yoshikawa:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Sarah R. Black:** Writing – review & editing, Project administration. **Timothy D. Nelson:** Writing – review & editing, Project administration. **Nathan A. Fox:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization. **Troller-Renfree Sonya:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kimberly G. Noble:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Molly A. Costanzo:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Greg J. Duncan:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization. **Debra S. Karhson:** Writing – review & editing, Project administration. **Michael K. Georgieff:** Writing – review & editing, Project administration. **Jennifer Mize Nelson:** Writing – review & editing, Project administration.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sonya Troller-Renfree reports a relationship with National Institute of Child Health and Human Development that includes: funding grants. Sarah Black reports a relationship with National Institute of Mental Health that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2026.101673.

Data availability

Data and Code Public

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