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ORIGINAL ARTICLE

From Adversity to Advantage: Uncertainty Priming Provides Executive Function Advantage in the Context of Childhood Adversity and Uncertainty

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Abstract
Adversity in childhood, which includes adverse life experiences such as abuse and neglect, but can also be more broadly understood to encompass household dysfunction and uncertainty, has been widely linked to poorer cognitive and mental health outcomes and is often interpreted within a deficit-model framework. However, emerging evidence suggests that certain forms of early adversity, particularly exposure to uncertainty, may also foster context-specific cognitive adaptations. Drawing on the specialisation–sensitisation framework, the present study examined whether exposure to childhood uncertainty and adverse life experiences is associated with enhanced executive function (EF) performance under uncertainty-primed conditions in adulthood. In a quasi-representative UK sample ($N=435$), participants completed validated measures of childhood uncertainty and childhood adversity alongside EF tasks assessing cognitive flexibility, inhibitory control, and working memory, following random assignment to either uncertainty or control priming. Higher childhood uncertainty and adversity exposure were associated with significantly better cognitive flexibility and inhibitory control performance under uncertainty priming, with no significant disadvantage under control conditions. An examination of the timing of adversity showed that early childhood exposure was associated with lower adult EF performance, regardless of priming context. Exposure to adversity in middle childhood was associated with a performance advantage under uncertainty priming conditions. Regarding adversity type, peer and family adversity were associated with overall cognitive flexibility performance disadvantages, whereas neglect exposure was associated with a cognitive flexibility performance advantage under uncertainty priming conditions. These findings add nuance to the discussion of impairments following childhood adversity and highlight the potential for adaptive calibration of cognitive systems. This work supports the need for context-sensitive assessments and interventions that acknowledge both the risks and the functional adaptations associated with early life adversity.

Public Relevance

Adults who experienced childhood adversity or uncertainty may perform better on executive function tasks when thinking about uncertain situations, suggesting potential hidden strengths shaped by early life experiences.

Key Findings

1. When primed for uncertainty, participants with exposure to childhood adversity and uncertainty perform better in executive function tasks.
2. Early-life adversity or uncertainty may thus enhance adults' executive function performance in unpredictable task contexts, revealing adaptive strengths shaped by challenging childhoods.
3. The long-term effects of childhood adversity may be more nuanced than dose-response models (i.e., higher adversity = higher impairment) suggest, with results indicating that both type and timing shape cognitive functioning in adulthood.

Keywords Adversity · ACEs · Adverse life experiences · Childhood adversity · Childhood uncertainty · Executive functions · Cognitive flexibility · Inhibitory control · Working memory · Priming

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Introduction

Children's right to freedom from violence, injury, abuse, neglect or negligent treatment, maltreatment and exploitation is enshrined within Article 19 of the United Nations Convention on the Rights of the Child (United Nations, 1989). However, recent prevalence rates still indicate that internationally a vast majority (75% in community samples; Pace et al., 2022; and 82% in at-risk samples; Pace et al., 2024) have experienced at least one such adversity in childhood. Adverse childhood experiences (ACEs) encompassing primarily abuse, neglect, and household dysfunction (Anda et al., 2010; Felitti et al., 1998) have been extensively associated with a broad range of negative life outcomes, including individuals' overall physical health and health-risk behaviours (e.g., cardiovascular disease (Godoy et al., 2021), autoimmune diseases (Macarenco et al., 2022 , obesity Schroeder et al., 2020), substance misuse disorders (alcoholism (Anda et al., 2002), illicit drug use (Dube et al., 2003), smoking (Ford et al., 2011) and mental health outcomes such as depression (Chapman et al., 2004), anxiety (Lee et al., 2020), suicidal ideation and attempts (Afifi et al., 2008). Furthermore, higher ACE exposure is associated with poorer neurodevelopmental and cognitive outcomes of affected individuals themselves (Guinosso et al. 2016; Katus et al. 2020, 2023a, b; Lloyd-Fox et al. 2019; Lund et al. 2020), and in some cases show intergenerational transmission through their impact on parenting practices (Narayan et al., 2021; Ogundiyun & Katus, 2025). Representing no exception to this well-documented link, the domain of executive functions (EF, i.e., cognitive flexibility, inhibitory control and working memory; Friedman & Miyake, 2017; Miyake et al., 2000) has been shown to be negatively impacted in individuals with higher ACE exposure (e.g., Lund et al., 2022). In part, this can be attributed to the relatively prolonged developmental time course associated with EF development, meaning that environmental insults across the entirety of childhood and adolescence may interfere with their typical developmental progression (Katus et al., 2023b). A wealth of literature documents potential harmful effects of ACEs within a deficit model (Houtepen et al., 2020; McLaughlin et al., 2019). However, a burgeoning body of research argues that adversity-led research often overlooks the adaptive nature of human development. Such views emphasise that individuals exposed to adversity during childhood cognitively adapt in response to stressful environments, such that their cognitive performance is highest when adverse experiences are evoked, but impaired under neutral performance demands (Ellis et al., 2022; Ellis et al., 2019; Young et al., 2022).

In the developmental literature, the term childhood adversity is used as a broad umbrella to describe early-life conditions that challenge normative development; however, it encompasses multiple related constructs that have historically been studied within separate research traditions. One such tradition focuses on adverse life experiences, commonly operationalised through measures of adverse childhood experiences (ACEs), which capture exposure to events such as abuse, neglect, and family dysfunction (Felitti et al., 1998; Finkelhor, 2020). A parallel body of work has examined childhood uncertainty or unpredictability, emphasising instability in environmental inputs, routines, and resource availability (Mittal et al., 2015; Young et al., 2018). Although contemporary theoretical frameworks increasingly conceptualise exposure to uncertainty as a core dimension of childhood adversity, these constructs have frequently been measured and analysed separately in empirical research (Ellis et al., 2022). In the present study, we adopt a pragmatic, integrative approach by conceptualising childhood adversity as encompassing both adverse life experiences and exposure to uncertainty, and by examining these as distinct but related forms of early adversity. This approach allows us to build directly on prior uncertainty-focused research while also extending these models to broader forms of childhood adversity.

One framework capturing this potential resilience-promoting process is the specialisation-sensitisation hypothesis which holds that cognitive development during times of uncertainty (specialisation) can enhance cognitive function in similar uncertain conditions in later life (sensitisation) and provides a refined view to the ubiquitous deficit model. Prior research has examined priming in the context of childhood uncertainty as one specific facet of early adversity. In the present study, we adopt a broader conceptualisation of adversity to capture a wider range of experiences that may shape children's socioemotional and cognitive development. By adversity, we refer to the widely accepted features of Adverse Childhood Experiences (ACEs). ACEs encompass potentially harmful events occurring before age 18, such as abuse, neglect, and forms of household dysfunction including parental mental illness, substance misuse, domestic violence, incarceration, or parental separation/divorce, as originally characterised in the seminal ACE study (Felitti et al., 1998). This broader framing allows us to examine how cumulative exposure to adverse experiences may influence children's responses beyond the narrower construct of uncertainty studied previously. Hereby, we explore the overall frequency of childhood adversity, as well as the roles of timing and type of adversity in the interplay of experimentally primed uncertainty condition and EF performance in adulthood. Drawing on questionnaire-based measures of childhood uncertainty (Young et al., 2018) and childhood adversity (Adverse Life Experience Scale [ALES]; Hawes et al., 2021; Lechowicz et al., 2018), we will assess the impact of childhood uncertainty, analogous to work presented in Young et al. (2018) and Mittal et al. (2015), before examining the relationship of childhood adversity frequency, timing and type in shaping EF performance under different priming conditions.

EF and Childhood Adversity: Timing of Exposure

The potential of childhood adversity to interfere with developmental processes across childhood is well-documented (e.g., Nelson & Gabard-Durnam, 2020). Insults and disruptions to normative development can loom particularly large when encountered early in development, where they more likely represent disruptions to the expectable environment, therefore being more likely to lead to permanent rather than merely transient alterations in brain structure and function (Nelson & Gabard-Durnam, 2020). This, in part, is due to their interference during the onset of a series of developmental cascades (Masten & Cicchetti, 2010), which in turn can disrupt subsequent development in the long run. Consistent with this notion, it has repeatedly been reported that exposure to adversity during early and middle childhood leads to worse outcomes with regard to cognitive development in general (Hambrick et al., 2019) and EF in particular (Schalinski et al., 2016). Furthermore, a shift from an adverse to a more nurturing environment, especially in infancy or early childhood, is linked to better EF than when adversity persists throughout development (McDermott et al., 2012). However, this improvement often falls short of enabling performance comparable to peers with no early adversity, underscoring the critical role of the earliest years in shaping long-term developmental trajectories.

An Alternative View: Specialisation Sensitisation Theory and the Importance of Performance Conditions

Adult cognitive performance in context of childhood adversity has been shown to be contingent on specific task demands, as well as conditions under which participants complete assessment protocols (e.g., Ellis et al., 2017). The specialisation-sensitisation hypothesis, grounded in evolutionary-developmental frameworks, suggests that cognitive development during times of uncertainty (specialisation) can enhance cognitive function in similar uncertain conditions later in life (sensitisation). Across several studies it has been demonstrated that when aspects of early life adversity are evoked in participants, this can affect their performance: For example, Mittal et al. (2015) found that exposure to unpredictable events positively correlated with task-switching abilities under uncertain conditions. Similarly, Young et al. (2018) found that adverse effects of ACEs on working memory were reversed in participants with a history of childhood uncertainty when tested under similar conditions in adulthood. This research suggests that cognitive adaptations stemming from early childhood uncertainty could be developed and leveraged in interventions. Further, Wang et al. (2023) investigated the interaction between childhood environmental unpredictability and primed uncertainty in enabling intuitive or deliberate visual search strategies. They reported that individuals with higher childhood unpredictability exhibited more effective search strategies under uncertainty cues, whereas the opposite was true for non-primed participants. Together, these studies underscore the importance of recognising the adaptive potential of EF in response to ACEs, suggesting that such adaptations might not only mitigate the harmful effects of adversity but could also lead to enhanced cognitive functioning under specific conditions.

Study Objectives and Hypotheses

The deficit model within the literature examining developmental outcomes following childhood adversity tends to eclipse the potential adaptive and resilience-promoting responses that may develop in response to early life adversity. Further, potentially nuanced effects of adversity timing or type, as well as performance context deserve a more detailed investigation. Considering the limitations in the existing research, this study examines the interaction between exposure to childhood adversity and cognitive development: in line with previous work highlighting the adaptive potential of individuals with exposure to childhood uncertainty in the context of the specialisation-sensitisation hypothesis (Mittal et al., 2015), this study probes the deficit model by examining how context, specifically priming for uncertainty, affects EF. Furthermore, this study addresses critical gaps in the literature by examining whether uncertainty priming confers a performance advantage in individuals with more varied early life-experiences (i.e., not only uncertainty, but childhood adversity more widely), incorporating objective measures of three core components of EF and accounting for adversity timing and type. The findings may inform both theoretical models and practical interventions to support individuals with a history of early life adversity.

The aims for this study are twofold. Firstly, we will assess the generalisability of findings presented in Young et al. (2018) and Mittal et al. (2015) by assessing specifically the impact of childhood uncertainty on EF under different priming conditions. Secondly, we assess whether prior findings expand to the broader construct of childhood adversity, and whether the temporal dynamics (i.e., timing of exposure) and the nature of exposure (adversity type), affect the interplay between childhood adversity and uncertainty, and EF performance under different priming conditions. By investigating these adaptations, the study aims to inform effective interventions and policies that recognise and leverage the unique strengths of individuals who have experienced high levels of early life adversity. Using these objectives as its foundations, this study will test three hypotheses to elucidate the relationship between childhood adversity and EF. Specifically:

H_1: Higher exposure to childhood uncertainty will be associated with better EF performance under uncertain priming conditions. Under control priming conditions participants with lower childhood uncertainty will show superior task performance.
H_2: Participants with higher levels of exposure to childhood adversity will show increased EF performance under uncertain priming conditions, whereas participants with low levels of exposure to childhood adversity will show superior performance in a control prime condition.
H_3: Adversity encountered in early childhood will be associated with poorer performance under a control prime condition, and with enhanced performance when primed for uncertainty.

Methods

Study Design

A multi-method experimental design was used, incorporating both a manipulated independent variable (priming condition) and observed individual difference variables indexing childhood uncertainty and childhood adversity. These variables were used to examine their effects on mean reaction time during tasks assessing cognitive flexibility, inhibitory control, and working memory. The experimental paradigm extended prior work by Mittal et al. (2015) and Young et al. (2018) by assessing the generalisability of findings beyond childhood uncertainty alone. Childhood adversity was operationalised using the Adverse Life Experiences (ALE) survey (Hawes et al., 2021; Lechowicz et al., 2018), allowing examination of uncertainty- and adversity-related effects across all core domains of EF. The study received ethical approval from the School of Human Sciences research Ethics Panel as well as the University Research Ethics Board at the University of Greenwich (Ethics number: 23.2.5.8).

Participants

Participants were recruited using systematic stratifying methods embedded in the Prolific platform (prolific.com), to obtain a quasi-representative sample of the adult UK population, regarding sex, age and socioeconomic status. To meet the inclusion criteria participants had to be over the age of 18, fluent in English, based in the UK, and able to complete the protocol in its entirety using either a laptop or desktop personal computer. Participants provided informed consent prior to any information being recorded. Participants were compensated at £6 to complete the 45-minute protocol. We aimed to recruit $N=400$, this sample size was determined in reference to effect sizes reported in previous work (Mittal et al., 2015), $r = .16$ on a cognitive flexibility task, requiring a sample size of 372 to detect at an alpha level of 0.05 to achieve >0.80 power.

Procedure

Data were collected using the cloud-based behavioural online research platform Gorilla (gorilla.sc; Anwyl-Irvine et al., 2020) in May 2024. Participants completed the experimental protocol independently online. First, participants were familiarised with each of the three cognitive tasks. Second, they were randomly allocated to either view the control or uncertainty primes (see 2.4 Materials and Measures). Third, they completed the first EF task (task order was randomised). Fourth, participants viewed an experimental manipulation booster, to reinforce the priming condition they had initially viewed, before completing the second EF task. Participants were then shown a second experimental manipulation booster, before completing the final cognitive EF task. Finally, two self-report questionnaires were completed pertaining to the participants' childhood environment.

Material and Measures

Uncertainty Primes Participants were randomly assigned to either view control primes or uncertainty primes. Each group was shown a slideshow resembling online news articles (Fig. 1). The slideshows were based on prior studies that validated and employed these techniques to experimentally evoke feelings of economic uncertainty or not (i.e., by viewing control stimuli). Stimuli were adapted from Mittal et al. (2015) and Young et al. (2018), with minor modifications to make them specific to a UK participant population (e.g., a US Dollar note was replaced by a Pound note, a graph of unemployment numbers was replaced to show recent UK data). The slideshows for both groups consisted of five individual images, each accompanied by a one-sentence caption and presented sequentially, with each being shown for 10 s. The uncertainty slideshow depicted a deteriorating

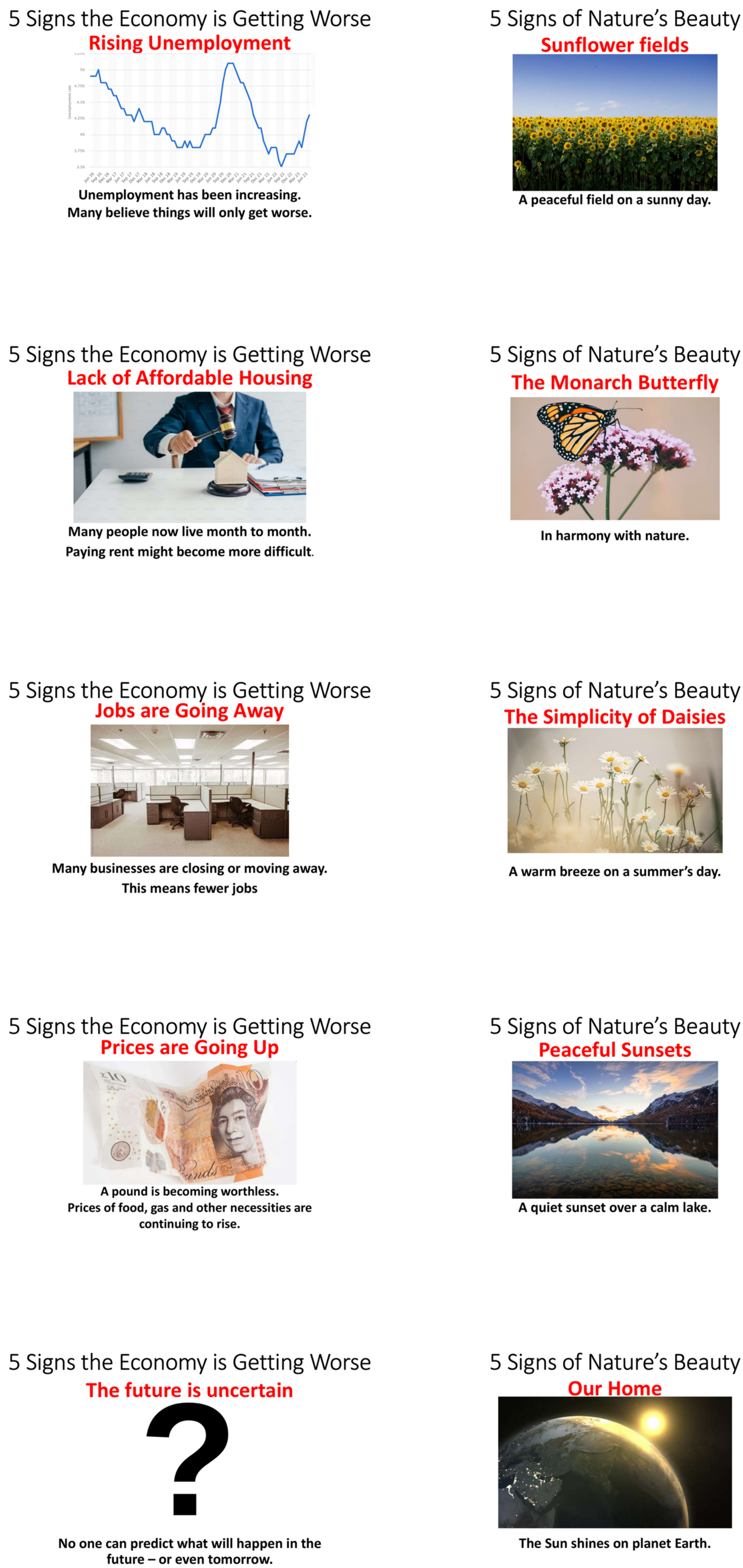

Fig. 1 Priming stimuli adapted from Young et al. (2018) showing uncertainty evoking stimuli on the left and control stimuli on the right. Each image was presented for 10 seconds.

and unpredictable economic environment, while the control slideshow showcased images exemplifying nature's beauty.

Manipulation Booster Upon completion of the first cognitive task and in-line with previous research participants completed a manipulation booster to maintain the desired state of uncertainty or control Hereby, participants were instructed to "Please cast your mind back to the short slide show you saw earlier: Provide one word that best describes the situation." This task was designed to re-engage participants with the material and prolong the emotional state we had intended to evoke. Following completion of the second EF task participants completed a second booster, where they were instructed to "Please cast your mind back to the short slide show you saw earlier: If you were to take a photo or draw a picture, what single image would best capture the emotion of the slide show?"

Executive Functions Experimental EF tasks were administered to assess cognitive flexibility, inhibitory control and working memory (depicted in Fig. 2). Task order was randomised. Cognitive flexibility was measured using an Alternate Switching Task (Fig. 2a). Participants were instructed to respond based on the location and properties (i.e., colour or shape) of visual stimuli presented on the screen. The shapes appeared either at the top or the bottom of the screen. When presented at the top of the screen participants needed to respond based on the shape's colour, whereas shapes appearing at the bottom of the screen required a response based on its form. After a fixation point was displayed for 1000ms, stimuli appeared and remained on screen until the participant made their response. The task consisted of 64 trials and lasted around 90 s.

Inhibitory control was measured using a Go/No-Go task (Fig. 2b, Gomez et al. (2007). Participants were directed to respond as quickly as possible to the direction of an arrow via button press. The colour of the arrow indicated whether a given trial was a Go or a No-Go trial. Stimuli were displayed in a random sequence with "Go" trials being presented at a probability of 66%. Trials started with a fixation point displayed for 500ms, the stimulus then remained on the screen for 2000ms or until the participants made their response. Task duration was approximately 90 s, consisting of 60 trials in total.

Working memory was measured using a 2-back task (Fig. 2c; Jaeggi et al., 2010), in which participants needed to indicate whether a given letter (presented for 500ms each) matched the letter seen two trials earlier via button press. Match trials were presented at a probability of 45%. The task lasted approximately 85 s and consisted of 58 trials.

Childhood Uncertainty and Adversity In reference to Young et al. (2018), participants reported the level of exposure to uncertainty during their childhood. Participants were asked to: "Please think back to your life when you were younger than 10. This time includes preschool, kindergarten, and the first few years of primary school." Participants then answered 8 items that assessed their level of exposure to unpredictability in childhood. These items were: (i) "My family life was generally inconsistent and unpredictable from day-to-day"; (ii) "My parent(s) frequently had arguments or fights with each other or other people in my childhood"; (iii) "My parents had a difficult divorce or separation during this time"; (iv) "People often moved in and out of my house on a pretty random basis"; (v) "When I woke up, I often didn't know what could happen in my house that day"; (vi) "My family environment was often tense and on edge"; (vii) "Things were often chaotic in my house"; and (viii) "I had a hard time knowing what my parent(s) or other people in my house were going to say." Each item was scored on a scale anchored at 1 = not at all to 7 = extremely, participants had the option not to answer. Mean scores were computed, yielding a possible response range of 1–7 on this measure. The childhood uncertainty scale (Young et al., 2018) has been shown to exhibit a 1-factor structure, with factor loadings ranging from 0.48 to 0.89.

To assess exposure to childhood adversity, we drew on the Adverse Life Experience Scale (ALES, Lechowicz et al.

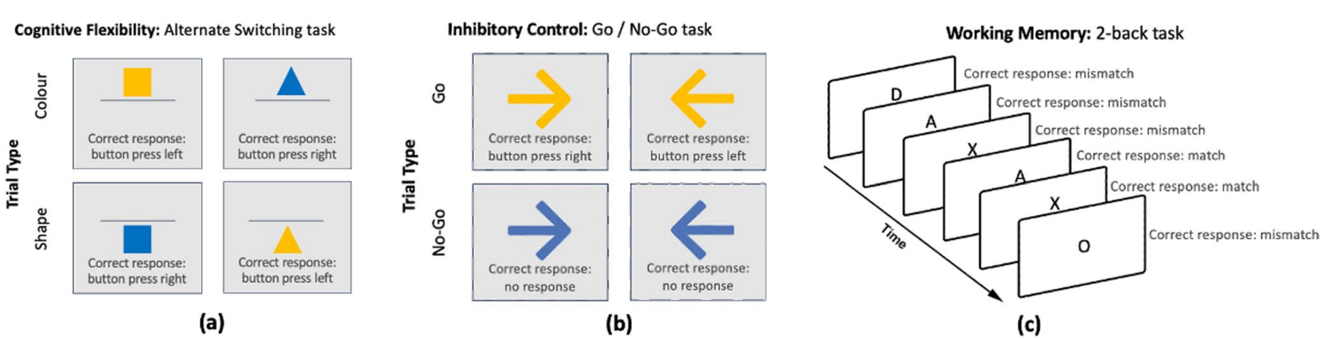

Fig. 2 Schematic of EF tasks used to assess cognitive flexibility (2a), inhibitory control (2b) and working memory (2c)

(2018); Hawes et al. (2021), which incorporates the ACE inventory developed by Felitti et al., (1998), along with modified items encompassing aspects such as exploitation or victimisation by peers, peer isolation, discriminatory experiences, and exposure to violence or war. For each of the 24 items, participants indicated (unless they preferred not to respond) when (if at all) they were exposed to a specific adverse experience, with response options 0–1 years, 2–3 years, 4–5 years, 6–8 years, and/or 9–12 years of age. The ALES has been found to exhibit good to high internal consistency (α=.86), and test–retest reliability over a 3–6-week period (ICC = .88) in its original validation sample of Australian families (Hawes et al., 2021). For our analyses on the timing effects of childhood adversity, we obtained mean scores to reflect exposure during early childhood (0–5 years, middle childhood (6–8 years) and late childhood (9–12) years, in line with prior use of this scale (Ogundiyun & Katus, 2025). Based on the current study, internal consistency of the childhood adversity timing scales demonstrated acceptable internal consistency (early childhood: α=.72, middle childhood: α=.77, late childhood: α=.76). For our analyses on the effects of childhood adversity type, mean scores were obtained across items measuring abuse (e.g., '*Have you been pushed*, *grabbed*, *slapped*, *or injured by an adult?*), neglect (e.g., *'Have you felt that no one in your family loved you or that no one thought you were important?'*), family adversity (e.g., *'Have you seen a family member get pushed*, *slapped*, *hit*, *punched*, *kicked*, *or threatened by another family or household member?'*), peer adversity (e.g., *'Have you felt lonely*, *or been rejected or excluded by peers?'*) and environmental adversity (e.g., *'Have you had to leave a country due to war*, *violence*, *and/or persecution?'*). Based on the current study, internal consistency for the childhood adversity type scale ranged from acceptable to good (family adversity: α=.79, environmental adversity: α=.79, peer adversity: α=.82, abuse: α=.88, neglect: α=.86).

Statistical Analyses

Due to limited prior assessment of the factor structure and conceptual equivalence of the childhood uncertainty and ALES, confirmatory factor analysis (CFA) was conducted to model the childhood uncertainty questionnaires and assess their measurement invariance across the domains of age and gender (for details see Supplementary Material). Following CFA and invariance analyses, data were further analysed using scaled mean scores for ease of interpretability (McNeish, 2024; McNeish & Wolf, 2020). Following examination of descriptive statistics, bivariate Pearson correlations were used to assess associations between the childhood uncertainty questionnaire and performance across the EF tasks, separately for each priming condition. Magnitudes of correlations were compared across EF tasks, to assess domain-specific effects of childhood uncertainty exposure. Subsequently, multiple multivariate regression models with predictors Priming Condition (Control/Uncertainty), and childhood uncertainty mean score were used to predict cognitive flexibility, inhibitory control and working memory reaction times. The same approach was taken for ALES mean scores. We then examined timing of adversity by correlating the mean scores across early, middle and late childhood with EF task performance, separately for each Priming Condition. We then used multiple multivariate regression models with predictors Priming Condition (Control/Uncertainty), adversity in early childhood, adversity in middle childhood and adversity in late childhood to predict cognitive flexibility, inhibitory control and working memory task performance. Lastly, we examined different adversity types, again first by correlational analyses separated for priming conditions and subsequent multivariate regression models. To correct for multiple testing, all correlational results were corrected via False Discovery Rate (FDR) procedures (Benjamini & Hochberg, 1995). All regression models used age as a covariate, due to its strong association with EF reaction times (Deary & Der, 2007). We hereby focussed on interaction effects between priming condition and childhood uncertainty or adversity exposure as well as on main effects of childhood uncertainty or adversity exposure independent of task condition. Significant main effects would suggest a broad influence on executive function performance regardless of priming, whereas a significant interaction would indicate that the priming condition itself confers a relative advantage or disadvantage on executive function task performance as a function of childhood exposure.

Results

Descriptive Statistics

A total of N=435 participants completed the study. The distribution of participant gender, age and ethnicity can be found in Table 1.

Presented below is a breakdown of participants' responses on the childhood uncertainty (Table 2) and the ALES questionnaires (Table 3 and Supplementary Table S1). Overall, 89.2% of participants reported having experienced at least one adverse life experience, and 61.8% reported having experienced four or more such experiences. EF scores in terms of reaction time and accuracy per task are displayed in Table 4. Prior to further analyses of the EF data, participants with implausibly low task accuracy were identified using an absolute threshold of < 0.20 accuracy

Table 1 Participant demographics per task condition and full sample

Characteristic	Control condition	Uncertainty condition	Total Sample
Sample Size, *N*	217	218	435
Gender, %			
Women	51.6	48.6	50.1
Men	46.5	48.6	47.6
Other / Prefer not to say	1.8	2.8	2.3
Age (years), %			
18–25	12.4	15.6	14.0
26–35	15.2	15.1	15.2
36–45	14.7	17.4	18.1
56–65	26.7	23.9	25.3
66–75	8.8	9.2	9.0
76+	1.4	1.4	1.4
Prefer not to say	0.9	0.0	0.5
Ethnicity, %			
Asian or Asian British	11.5	6.9	9.2
Black, African, Caribbean, or Black British	1.8	5.0	3.5
Multiple ethnic groups	1.8	2.8	2.3
White	84.9	85.3	85.0

Values are percentages unless otherwise indicated; sample sizes (*N*) are reported as counts. Percentages may not sum to 100 due to rounding

Table 2 Descriptive statistics for responses on the childhood uncertainty scale per priming condition

Item	Control condition M±SD	Uncertainty condition M±SD
1. My family life was generally inconsistent and unpredictable from day-to-day.	2.25±1.76	2.8±1.85
2. My parent(s) frequently had arguments or fights with each other or other people in my childhood.	1.91±1.55	2.07±1.61
3. My parents had a difficult divorce or separation during this time.	2.79±1.90	3.00±2.0
4. People often moved in and out of my house on a pretty random basis.	1.69±1.68	2.15±2.0
5. When I woke up, I often didn't know what could happen in my house that day.	1.27±0.80	1.28 ± 0.90
6. My family environment was often tense and on edge.	2.53±1.80	2.73±1.88
7. Things were often chaotic in my house.	2.24±1.63	2.39±1.77
8. I had a hard time knowing what my parent(s) or other people in my house were going to say.	2.28±1.64	2.45±1.78

M = mean, *SD* = standard deviation

Table 3 Total Adversity Endorsements per Developmental Period and Condition

Developmental Period	Control Condition (Total Endorsements)	Uncertainty Condition (Total Endorsements)
Early childhood (0–5 years)	942	1,027
Middle childhood (6–8 years)	243	290
Late childhood (9–12 years)	362	600

Values represent the total number of item-level adversity endorsements within each developmental period. These totals reflect the number of endorsed ALES items, not the number of individual participants. Item-level frequencies for all 24 ALES items are provided in Supplementary Table S1

Table 4 Descriptive statistics for reaction times and accuracy on EF tasks per priming condition

Task	Reaction Time (ms) Control M±SD	Reaction Time (ms) Uncertainty M±SD	Accuracy Control M±SD	Accuracy Uncertainty M±SD
Cognitive Flexibility	1145.8±412.4	1131.8±414.7	0.87 ± 0.14	0.87 ± 0.14
Inhibitory Control	519.9±130.6	503.8±116.0	0.98 ± 0.08	0.97 ± 0.11
Working Memory	813.0±211.3	822.9±202.8	0.85 ± 0.16	0.83 ± 0.16

Reaction times are reported in milliseconds. Accuracy reflects proportion correct. *M* = mean; *SD* = standard deviation

on any EF task, indicating a likely failure to understand task instructions. This procedure resulted in the exclusion of four participants. Initially, reaction time data exhibited positive skewness beyond acceptable levels (cognitive flexibility: skewness = 2.55; inhibitory control: skewness = 2.19; working memory: skewness = 2.48), with values exceeding the commonly accepted threshold of ±2. Following outlier removal, skewness was reduced to acceptable levels (cognitive flexibility: skewness = 0.58; inhibitory control: skewness = 0.42; working memory: skewness = 0.50), indicating improved distributional properties of the data.

Participants' responses to the manipulation boosters were examined and are visualised in Fig. 3.

Childhood Uncertainty and Adult EF in Context of Uncertainty Priming

First, reaction times (RTs) were calculated using all trials (correct and incorrect), as RTs on error trials still reflect underlying attentional and decision processes (Luce, 1991; Ratcliff, 1978). Omitting error trials can bias RT estimates by disproportionately removing data from individuals with lower accuracy (Baayen & Milin, 2010; Ulrich & Miller, 1994). Including all available trials increases reliability and statistical power, particularly in developmental samples (Jensen, 2006), and aligns with established modelling approaches in which both correct and incorrect RTs provide essential information about processing dynamics (Ratcliff & McKoon, 2008).

We next proceeded to test our first hypothesis, namely that higher exposure to childhood uncertainty would be

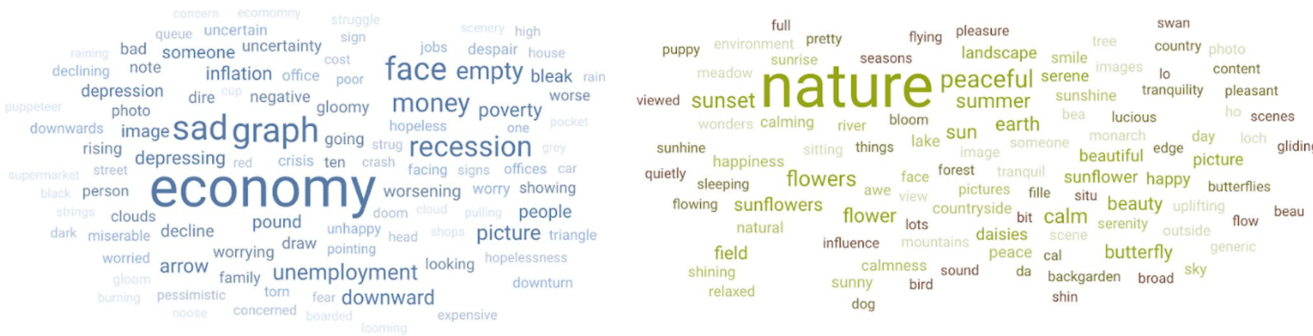

Fig. 3 Participant responses to manipulation boosts asking them to cast their mind back to and summarise the priming material in one word or image

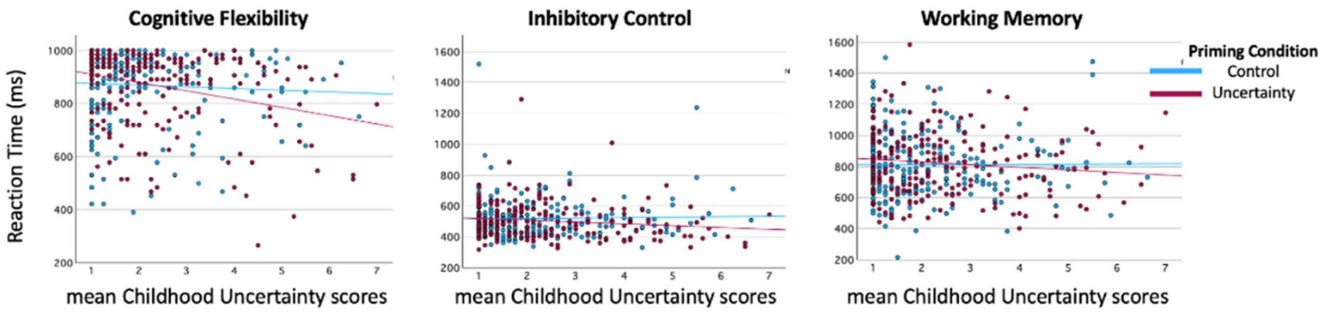

Fig. 4 Reaction time per EF task and mean childhood uncertainty score split by priming condition. Reaction time in the control condition did not differ significantly relative to childhood uncertainty level, whereas in the uncertainty prime condition significant negative correlations were found for the cognitive flexibility and inhibitory control, but not the working memory tasks

associated with better EF performance under uncertain priming conditions, while under control prime conditions participants with lower levels of childhood uncertainty would show superior task performance. Bivariate Pearson correlations showed no associations between childhood uncertainty and cognitive flexibility ($r=-.06$, $n=217$, $p_{FDR} = 0.200$), inhibitory control ($r = .03$, $n=217$, $p_{FDR} = 0.353$) or working memory scores ($r=.01$, $n=217$, $p_{FDR} = 0.472$) in the control prime condition. Magnitudes of these correlations did not differ between tasks (cognitive flexibility vs. inhibitory control: $z=-0.86$, $p_{FDR} =0.389$; cognitive flexibility vs. working memory: $z=-0.64$, $p_{FDR} = 0.522$; inhibitory control vs. working memory: $z = 0.22$, $p_{FDR} = 0.826$). When primed for uncertainty, there were significant negative correlations between childhood uncertainty and all EF tasks (cognitive flexibility: $r=-.30$, $n=218$, $p_{FDR} < 0.001$; inhibitory control: $r=-.14$, $n=218$, $p_{FDR} = 0.020$; working memory: $r=-.11$, $n=218$, $p_{FDR} = 0.049$). Associations between working memory scores and childhood uncertainty were significantly smaller in magnitude compared to the cognitive flexibility task (cognitive flexibility vs. working memory: $z = -2.01$, $p_{FDR} = 0.044$). Via multiple multivariate regression with predictors Condition (Control/Uncertainty), childhood uncertainty mean scores and outcomes EF task (cognitive flexibility/ inhibitory control/ working memory), covarying for age, we found significant interactions for childhood uncertainty and cognitive flexibility scores ($F(33,353)=1.74$, $p = .008$, $\eta_p^2=0.14$) and inhibitory control scores (F $(33,353)=1.79$, $p = .006$, $\eta_p^2=0.15$), but not working memory scores (F $(33,353)=1.06$, $p = .379$, $\eta_p^2=0.09$). In sum, under control prime conditions, there was no link between childhood uncertainty and any of the EF tasks. Under uncertain task conditions, higher uncertainty was associated with faster cognitive flexibility and inhibitory control, but not working memory, reaction times, indicating a potential performance advantage of participants with higher childhood uncertainty when primed for uncertainty. Results are visualised in Fig. 4.

We thus found partial evidence for our hypothesis: while participants with lower childhood uncertainty in the control prime condition did not outperform those with higher childhood uncertainty, we did find a performance advantage of participants with higher childhood uncertainty in the uncertainty priming condition. This advantage was present for the cognitive flexibility and inhibitory control, but not the working memory task.

Childhood Adversity and Adult EF in Context of Uncertainty Priming

Analogous to the analysis examining childhood uncertainty presented above, we next focussed on the broader concept of childhood adversity by testing our hypothesis that participants with higher levels of childhood adversity would show increased EF performance under uncertain priming conditions, whereas participants with lower exposure to childhood adversity would show superior performance in a control prime condition. First, we examined associations between childhood adversity and all EF tasks, separately for the uncertainty and control prime condition. No associations were found between childhood adversity and EF performance under the control priming condition (cognitive flexibility: $r=-.04$, $n=216$, p_{FDR} = 0.299; inhibitory control: r = .01, $n=216$, p_{FDR} = 0.449; working memory: $r=-.02$, $n=216$, p_{FDR} = 0.378). Magnitudes of these correlations did not differ between tasks (cognitive flexibility vs. inhibitory control: $z=-0.46$, p_{FDR} = 0.646; cognitive flexibility vs. working memory: $z=-0.15$, p_{FDR} = 0.880; inhibitory control vs. working memory: z = 0.31, p_{FDR} = 0.757). Under uncertainty prime conditions however, following a similar pattern across EF tasks as the previous analyses on childhood uncertainty, associations were found between exposure to childhood adversity and cognitive flexibility ($r=-.22$, $n=216$, $p_{FDR} < 0.001$) as well as inhibitory control ($r=-.17$, $n=216$, p_{FDR}= 0.007), but not working memory ($r=-.05$, $n=216$, p_{FDR} = 0.234). Notably, despite these differences in significance levels, the magnitude of the correlations did not differ significantly across the tasks (cognitive flexibility vs. inhibitory control: $z=-0.6$, p_{FDR} = 0.549; cognitive flexibility vs. working memory: z = -1.81, p_{FDR} = 0.070; inhibitory control vs. working memory: z = -1.21, p_{FDR} = 0.226). Using multiple multivariate regression with predictors Condition (Control/Uncertainty), ALEs scores and EF tasks (cognitive flexibility/inhibitory control/working memory) as outcomes, covarying for age, we found significant interactions for childhood adversity and cognitive flexibility scores (F(53, 130) = 1.61, p = .006, η_p^2 = 0.15) and inhibitory control scores (F(53, 130) = 1.57, p = .010, η_p^2 = 0.14), but not working memory scores (F(53, 130) = 1.24, p = .132, η_p^2 = 0.07). Results are visualised in Fig. 5.

In sum, these findings mirror and expand those of the childhood uncertainty questionnaire above: under control prime conditions, there was no link of ALEs score with any EF task. Under uncertain task conditions, higher uncertainty was associated with faster cognitive flexibility and inhibitory control reaction times, indicating a potential performance advantage of participants with higher childhood adversity to benefit from uncertain task demands. This indicates that priming for uncertainty might also confer a performance advantage in participants with higher childhood adversity more generally.

Developmental Timing of Childhood Adversity

To test our hypothesis that exposure to adversity in early childhood would have more pronounced effects in shaping either a performance advantage or disadvantage under uncertainty prime or control prime conditions, respectively, we obtained mean ALES scores for early childhood (0–5 years), middle childhood (6–8 years) and late childhood (9–12 years), in reference to prior work employing age groupings of the ALES scale (Ogundiyun & Katus, 2025). We first examined bivariate Pearson correlations separately for participants in the control prime and the uncertainty prime conditions. Hereby, in the control prime condition no significant associations were found for any of the EF tasks and ALES scores in early, middle or late childhood. However, in the uncertainty prime condition we found associations between cognitive flexibility performance and exposure to adversity in early, middle and late childhood, as well as inhibitory control performance and exposure to adversity in middle and late childhood (Table 5).

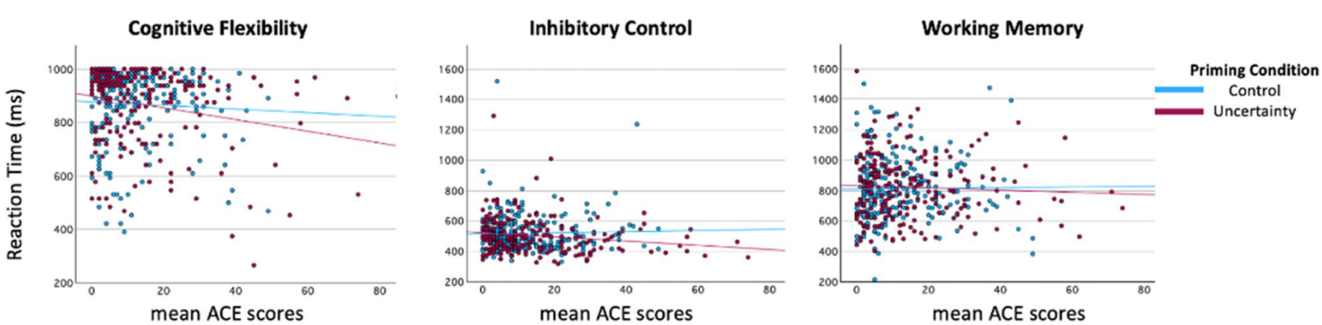

Fig. 5 Reaction time per EF task and mean ALEs score split by priming condition. Reaction time in the control prime condition did not differ significantly relative to childhood uncertainty level, whereas in the uncertainty prime condition significant negative correlations were found for the cognitive flexibility and inhibitory control, but not the working memory tasks

Table 5 Correlations between exposure to adversity during early, middle and late childhood across EF domains per priming condition

EF domain	Early childhood Control (n=217)	Early childhood Uncertainty (n=218)	Middle childhood Control (n=217)	Middle childhood Uncertainty (n=218)	Late childhood Control (n=217)	Late childhood Uncertainty (n=218)
Cognitive Flexibility	r=−.05, p = .509	r=−.19, p = .005**	r=−.01, p = .905	r=−.25, p = .001**	r=−.15, p = .053	r=−.15, p = .027*
Inhibitory Control	r = .03, p = .698	r=−.13, p = .061	r=−.03, p = .648	r=−.15, p = .031*	r = .02, p = .770	r=−.20, p = .003**
Working memory	r=−.03, p = .618	r=−.06, p = .365	r=−.02, p = .806	r=−.09, p = .199	r = .04, p = .587	r=−.02, p = .760

r=Pearson correlation coefficient. All p values reported in the table are false discovery rate–adjusted (Benjamini & Hochberg, 1995). *p_{FDR} <0.05, ** p_{FDR} <0.01

Table 6 Correlations between adversity type across EF domains per priming condition

EF domain	Abuse Control (n=217)	Abuse Uncertainty (n=218)	Neglect Control (n=217)	Neglect Uncertainty (n=218)	Family adversity Control (n=217)	Family adversity Uncertainty (n=218)	Peer adversity Control (n=217)	Peer adversity Uncertainty (n=218)	Environmental adversity Control (n=217)	Environmental adversity Uncertainty (n=218)
Cognitive Flexibility	r = − .08, p = .217	r = − .19**, p = .005	r = − .09, p = .191	r = − .13, p = .056	r = − .07, p = .314	r = − .19**, p = .005	r = − .02, p = .748	r = − .18**, p = .008	r = .06, p = .382	r = − .18*, p = .010
Inhibitory Control	r = .03, p = .690	r = − .13, p = .051	r = − .03, p = .700	r = − .09, p = .193	r = .08, p = .220	r = − .14*, p = .037	r = − .03, p = .700	r = − .14*, p = .038	r = − .14, p = .052	r = − .15*, p = .026
Working memory	r=−.06, p = .382	r = − .08, p = .237	r = − .01, p = .894	r = − .07, p = .279	r = .09, p = .195	r = − .07, p = .289	r = − .01, p = .920	r = − .02, p = .796	r = − .08, p = .268	r = − .03, p = .624

r=Pearson correlation coefficient. All p values reported in the table are false discovery rate–adjusted (Benjamini & Hochberg, 1995). *p_{FDR} <0.05, ** p_{FDR} <0.01

Via multiple multivariate regression with predictors Priming Condition (Control/Uncertainty), exposure to adversity in early, middle and late childhood and outcomes EF task (cognitive flexibility/inhibitory control/working memory), covarying for age, we found main effects for exposure to adversity in early childhood and performance on the cognitive flexibility, $F(17, 335)=1.99$, p = .014, $\eta_p^2=0.09$, and inhibitory control, $F(14, 335)=3.14$, p < .001, $\eta_p^2=0.12$, tasks. We further found interaction effects of Priming Condition and exposure to adversity in middle childhood for the cognitive flexibility, $F(16,335)=1.77$, p = .035, $\eta_p^2=0.08$, and inhibitory control, $F(16,335)=1.67$, p = .047, $\eta_p^2=0.07$, tasks. These results may indicate a broad deleterious effect of early childhood adversity on EF task performance (with working memory as the exception) that remains unaffected by task priming conditions. Exposure to adversity during middle childhood may be associated with altered EF responses that are, however, susceptible to task context.

Type of Childhood Adversity

Lastly, we examined associations between adversity type and EF performance. We first examined correlations between mean scores across the five adversity-types (abuse, neglect, family adversity, peer adversity, environmental adversity) and EF task performance across the two priming conditions. In the control prime condition, there were no associations that survived multiple comparison correction between any adversity type and EF task. In the uncertainty prime condition, we found some links with cognitive flexibility (for abuse, family, peer and environmental adversity) and inhibitory control (for family, peer and environmental adversity). Correlations are summarised in Table 6.

Next, we ran a multivariate model with adversity type (abuse, neglect, environmental adversity, peer adversity and family adversity) and Priming Condition (Control/Uncertainty) predicting cognitive flexibility, inhibitory control and working memory, controlling for age. For cognitive flexibility, main effects were found for peer adversity, $F(11,318)=1.89$, p = .040, $\eta_p^2=0.06$, and family adversity, $F(21,318)=1.73$, p = .025, $\eta_p^2=0.10$. For cognitive flexibility, neglect showed a weak interaction effect with Priming Condition, $F(6,318)=2.33$, p = .032, $\eta_p^2=0.04$.

Taken together, these findings may indicate that family and peer adversity are more strongly linked with cognitive flexibility in such a way that is not necessarily mediated by task context. In terms of the interaction effects, results indicate that neglect was associated with a performance advantage under uncertainty prime conditions.

Discussion

Childhood adversity remains a major determinant for population health and wellbeing worldwide (Pace et al., 2022). While intervention efforts focused on minimising exposure to childhood adversity continue and are beginning to show a decrease of certain adversity types (Finkelhor, 2020), complementary efforts must be made to understand the health and neurodevelopmental consequences for affected individuals. To those exposed to childhood adversity, uncertainty is hypothesised to cue the potential presence of environmental threats, eliciting response styles resulting from neural specialisation in adverse contexts (Mittal & Giskevicius, 2016). Here, we contribute to theoretical accounts highlighting both vulnerability and adaptation following childhood adversity. Specifically, while early childhood adversity was associated with lower adult EF performance across conditions, our findings indicate that performance advantages among individuals with higher childhood uncertainty and adversity emerged only under uncertainty-primed task contexts, and not under control conditions. In a quasi-representative, UK-based sample we anticipated a performance deficit in adult EF in context of higher childhood uncertainty and adversity, but a possible performance advantage when participants' mindset was primed for uncertainty. In partial support of our hypotheses, across analyses higher exposure to childhood uncertainty and adversity was associated with better performance on cognitive flexibility and inhibitory control tasks under uncertainty priming, with no significant differences under neutral conditions. This finding may be attributable to the overall more normative, non-clinical range of childhood uncertainty and adversity exposure in our sample, which may not have produced marked EF deficits under neutral task conditions. As highlighted in prior meta-analyses, this finding may be interpreted in line with threshold models of adversity exposure (Evans et al., 2013), that suggest that only once there is an accumulation of multiple adversities do cognitive deficits become apparent. Within this general population sample, the observed associations are consistent with a linear pattern across the range of adversity represented; however, work situated within developmental psychopathology proposes that relationship between adversity and EF may follow an inverted U-shaped function at higher levels of exposure (Oshri, 2023; Oshri et al., 2024). Accordingly, while low-to-moderate exposure to childhood adversity may support adaptive, context-sensitive advantages under certain conditions, higher levels of adversity are likely to exert more globally detrimental effects on executive functioning. Our findings do suggest, however, that in the absence of severe exposure, uncertainty priming might hold benefits to participants more used to environmental adversity.

Lastly, effects on EF showed consistent associations with cognitive flexibility and inhibitory control, but fewer clear links with working memory. This is in contrast to prior work in this field (e.g., Young et al., 2018), and may be attributable to the difference in tasks employed across studies, as well as the demands of the task employed here, which may not have served to optimally reveal individual differences in the sample. This pattern suggests that executive function components may be differentially sensitive to contextual cues. Cognitive flexibility and inhibitory control are particularly reliant on rapid adaptation to changing task demands and the regulation of prepotent responses, processes that may be selectively tuned by repeated exposure to unpredictable environments (Mittal et al., 2015). From a specialisation–sensitisation perspective, such components may be more readily calibrated by uncertainty cues that signal the need for vigilance, behavioural adjustment, and efficient control. By contrast, working memory may be less directly engaged by uncertainty priming in the present task context, or may require sustained or domain-specific environmental input to show comparable adaptive effects (Young et al., 2018). These task-specific differences align with developmental accounts of executive function as a set of partially dissociable processes with distinct developmental trajectories and experiential sensitivities (Katus et al., 2023b). Furthermore, these findings contribute to a developing body of research suggesting that cognitive flexibility may function as a meta-competence supporting executive functioning across the life course and underpinning cognitive development (Birney & Beckmann, 2022; Yu et al., 2019).

With regard to adversity timing, prior work highlights the importance of early childhood as a sensitive developmental period, often associated with greatest developmental impairments (Masten & Cicchetti, 2010). Our data provided support of this notion, showing that early childhood adversity is associated with lower adult EF performance, regardless of priming condition. In the other hand, middle childhood appeared particularly sensitive to priming context. This pattern may suggest that adversity during middle childhood fosters adaptive, context-sensitive cognitive tuning, while early adversity disrupts foundational neurodevelopmental processes in ways that are less amenable to later environmental modulation, underlining the importance of fostering neurocognitive development during the early years (Attanasio et al., 2022). Early childhood is also a period in which children are largely buffered by caregivers, meaning that adversity encountered at this stage may interfere with the development of foundational executive and regulatory systems rather than calibrate them. By middle childhood, children interact more directly with their environments, rendering adversity-related cues more reliable indicators of the contexts they must navigate. Accordingly, sensitisation processes during this period may support adaptive tuning of cognitive systems. This developmental distinction helps explain why early adversity is associated with more global EF disadvantages, whereas middle-childhood adversity predicts enhanced EF performance under conditions of uncertainty.

It is important to acknowledge that the timing and type of adversity may not be fully independent. Certain forms of adversity, such as neglect or family conflict, are more likely to occur in early childhood, whereas peer-related adversities or discrimination are more common later in development. As a result, observed timing effects may partially reflect the typical developmental clustering of specific adversity types. This co-occurrence should be considered when interpreting age-related patterns, and future work would benefit from designs that can more explicitly disentangle the developmental timing and qualitative nature of adverse experiences.

Finally, analyses on adversity types showed that peer and family adversity were associated with lower adult cognitive flexibility performance, regardless of task context. Neglect on the other hand, was associated with higher EF performance under uncertainty priming conditions. These findings further contribute to the emerging literature on different developmental sequalae of deprivation versus threat-based exposures, pointing to a nuanced interaction between early-life adversity and environmental context in shaping adaptive EF responses. In essence we here present findings in support that both childhood uncertainty and adversity can lead to advantage in the right contexts.

In particular, our findings suggest that individuals exposed to early childhood adversity oftentimes perform at levels exceeding those without such histories, provided the task context mimics conditions under which neural specialisation occurred. This challenges the view that adversity necessarily impairs cognitive potential and instead highlights the importance of performance context and adaptive functioning. Our use of the ALES, which captures a broader and more fine-grained range of experiences, including the type, timing, and chronicity of exposure, may offer a more comprehensive alternative to traditional ACE measures. By emphasising the importance of task context we hope that this work not only informs future intervention efforts but also contributes to a growing body of research that seeks to move beyond cumulative models of adversity and towards a more nuanced, individualised view of the effects of childhood adversity.

Strengths, Limitations and Future Research

Strengths of this study include the quasi-representative UK sample, the exploration of childhood adversity's temporal dynamics and exposure type, which provides a more nuanced understanding of how specific types of adversity impact EF across development. The study also takes a broader perspective by examining the wider construct of childhood adversity, therefore building on prior work examining the specific impact of childhood uncertainty, contributing to a more comprehensive view of how early experiences influence cognitive outcomes. Finally, our objective task-based protocol reduces some of the potential informant bias associated with EF self-report (Compton et al., 2024).

Self-report measures of childhood uncertainty and childhood adversity are subject to inherent bias, particularly given that participants were required to recall events that may have occurred several decades earlier. Recall accuracy may also vary across developmental periods, with experiences from later childhood potentially remembered more precisely than those from early childhood. In addition, some relevant dimensions of adversity, such as severity and chronicity, were not assessed. Future research would benefit from triangulating self-report data with additional informants, such as caregivers or child support services, to reduce informant bias. Although the ALEs measure allowed for a more detailed assessment of the occurrence and developmental timing of childhood adversity than binary ACE checklists, it does not capture the intensity or frequency of experiences, limiting inferences about the strength of exposure. Given the subjective and interpretative nature of adversity recall, these dimensions may be difficult to quantify reliably; nonetheless, future research would benefit from integrating measures that capture both occurrence and severity, and from complementary qualitative approaches that allow for deeper exploration of lived experience.

In addition, the cross-sectional design of the present study further limits inferences about the developmental timing of executive function (EF) advantages or disadvantages. Longitudinal or prospective approaches, including examination of concurrent exposure to adversity and the development of executive control (cf. McLaughlin et al., 2014), would help to clarify developmental trajectories, albeit with notable ethical and practical challenges. We also acknowledge that the wide age range of the sample may have introduced additional variability in EF performance and increased the likelihood of age-related recall bias. However, this age span was intentionally selected to approximate a quasi-representative UK adult sample.

Finally, although EF outcomes showed consistent associations with cognitive flexibility and inhibitory control, links with working memory were less evident, diverging from some prior findings (e.g., Young et al., 2018). Such discrepancies may reflect differences in task demands across studies, including the possibility that the tasks employed here were not optimally sensitive to individual differences in working memory.

Additionally, we acknowledge that the priming task was administered in a standardised experimental context, which may elicit different reactions than uncertainty priming encountered in participants' everyday lives. In addition, the priming stimuli differed not only in content (uncertainty vs. nature themes) but also in valence. This may have exaggerated priming effects by inducing negative versus positive emotional states that extend beyond the intended uncertainty manipulation. Future research should therefore examine whether these effects replicate when using stimuli that are more closely matched (e.g., Young et al., 2018). Furthermore, future research would benefit from incorporating a wider set of contextually rich, ecologically valid uncertainty cues (e.g., interpersonal unpredictability, social instability, environmental change) or from using immersive methods that more closely approximate lived experience.

Similarly, a further limitation of the present study is the absence of a direct, state-based manipulation check assessing participants' emotional state following the priming task. Although participants' one-word or image summaries of the slideshow provided indirect insight into how the priming stimuli were interpreted, this approach cannot substitute for a validated manipulation check or capture momentary affective responses. Future studies would benefit from incorporating brief state-based measures alongside the priming procedure to more precisely assess its experiential impact.

Conclusion

Our study highlights that, in addition to well-documented cognitive performance deficits associated with childhood adversity and uncertainty, task context matters: specifically, we show that priming participants for uncertainty is associated with better adult EF performance. Taken together, our findings contribute to the growing body of literature on how childhood adversity shapes cognitive outcomes in adulthood and underscore the importance of considering not just the presence of adversity, but also its timing, and the context in which it is later encountered. Future research should continue to explore the real-life conditions under which individuals exposed to childhood adversity can harness resilience, as well as the mechanisms through which uncertainty priming may offer unexpected cognitive advantages. These insights may hold promise for interventions aimed at enhancing cognitive performance and adaptive functioning in individuals with histories of adversity.

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Author Contributions The concept and methodology of this paper were developed by Benjamin Sigsworth and Laura Katus. Software implementation, formal analysis, and data curation were undertaken by Benjamin Sigsworth, Laura Katus and Tobias Katus. Data validation was carried out by Benjamin Sigsworth and Tobias Katus. The investigation was conducted by Benjamin Sigsworth. Resources for this study were provided by Laura Katus and Peter Collins. The original manuscript was prepared by Benjamin Sigsworth and Laura Katus, all authors provided feedback on previous versions of the manuscript. Visualisation was developed by Benjamin Sigsworth, Laura Katus and Tobias Katus. Project administration was coordinated by Benjamin Sigsworth. Project supervision was jointly provided by Tobias Katus, Laura Katus and Peter Collins. Funding acquisition was led by Laura Katus in collaboration with Benjamin Sigsworth.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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