Experience of maltreatment blunts the calibration of control beliefs

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Significance Statement

Childhood maltreatment considerably increases risk of mental health problems in later life by impacting distinct neurocognitive systems. Here we investigated the impact of childhood maltreatment on control beliefs and their relation to stress and exploration. We used a novel experimental task manipulating two external cues of control (task controllability and performance feedback) in a large sample of adults (N = 477) with and without a history of childhood maltreatment. Our results show that while task performance improved over time for both groups, maltreated participants used this less to update their control beliefs. Further, only control participants leveraged positive performance feedback to reduce stress and increase exploration. We suggest such a profile confers vulnerability to mental health problems.

Experience of maltreatment in childhood profoundly impacts a plethora of neurocognitive systems, significantly increasing risk for later mental health problems. Here we investigate how childhood maltreatment shapes control beliefs and their relationship with stress and exploration in adulthood. We used a recently developed task, the Wheel Stopping (WS) task, to measure and manipulate control beliefs and stress, and combined this with a novel self-report measure of exploration in a sample of 477 adults with and without experience of childhood maltreatment (matched on age, gender and socioeconomic status). The WS task utilises two between-subjects manipulations of control: task controllability (high vs low), and performance feedback (relative positive vs relative negative). We show that despite similar task performance, maltreated participants displayed lower levels of control beliefs compared to controls and that while task performance improved over time for both groups, maltreated participants used this less to update their control beliefs. Further, whereas both groups responded equally to the task manipulations, only controls leveraged relative positive feedback to reduce task-related stress and increase goal-directed exploration. We conclude that maltreatment blunts the calibration of control beliefs, informing both stress and goal-directed exploration, likely increasing vulnerability to psychopathology.

Childhood maltreatment, defined as experiences of physical, sexual, emotional abuse or neglect, considerably increases risk of mental health problems in later life (1). Mental health problems caused by maltreatment are often more severe (2), complex (3) and treatment-resistant (4). The diversity of mental health outcomes associated with childhood maltreatment, including depression, anxiety, substance use, borderline personality disorder and schizophrenia (5–8), is reflected by its association with the general psychopathology factor (9) and alludes to common transdiagnostic neurocognitive mechanisms. The theory of latent vulnerability posits that exposure to maltreatment calibrates neurocognitive systems to promote short-term advantages. Such adaptations however are often poorly optimised for normative environments; a mismatch which can confer heightened risk for psychopathology (10–13). Probing the neurocognitive processes affected by childhood maltreatment may improve prediction and treatment of mental health problems (10, 11, 13), and to date, a range of candidate neurocognitive systems have been investigated including reward processing, autobiographical memory, executive functioning and stress (10, 13–20). Here we focus on control beliefs, which we use to refer to estimations of control over current environments, and their role in calibrating stress systems and goal-directed exploration as a marker of latent vulnerability.

An individual has control when voluntary actions can achieve desired or avoid undesired contingent outcomes. It has been argued that control constitutes a fundamental human need (21–23), explaining its pivotal role in organising cognition, motivation, behaviour and mental health (24–26). Experiences of control result in estimations, or *beliefs,* of control over current and future situations, with such beliefs subserving environmental exploration, proactive and goal-directed behaviours, and stress regulation (25, 27). Decades of cross-species research on learned helplessness highlight the motivational significance of control over one’s social and physical environment (27), shaping developmental outcomes such as mental health and well-being (26, 28, 29). Whilst experiences shape control beliefs throughout life, a plethora of evidence suggests their foundations are laid early in life via interactions with caregivers (25, 26, 30). For example, in infants, reduced contingent interactions with caregivers significantly increases negative affect (31) while contingent interactions with a stranger can buffer against the separation-induced cortisol response (32). Moreover, parental hostility elicits more negative affect and helplessness behaviours in children, and less motivation and hopefulness in problem solving tasks (33, 34). A hallmark of maltreating environments is the absence of contingency between actions and reliably eliciting positive outcomes (as is the case with neglect) and / or the inability to avoid negative outcomes (as is the case with abuse) within caregiver relationships. As such, childhood maltreatment may undermine the development of emerging control beliefs (35), inducing a differential sensitivity to the effects of environmental controllability. Indeed, childhood maltreatment has been shown to impact questionnaire-based measures of perceived control, with higher levels of external locus of control (beliefs that external forces have a greater influence on life outcomes) following experiences of neglect (36). Importantly, such altered beliefs impact the ability to learn control in reinforcement learning tasks (37) and mediate the link between maltreatment and internalising symptoms (38, 39). However, it is currently unclear i) if and how maltreatment impacts the ability to update control beliefs over time, and ii) whether maltreatment modulates the impact of environmental cues of control on stress and exploration.

Control beliefs effectively orchestrate individuals' self-regulation and interaction with their environment. For instance, a wealth of work in animals has shown that control over stressors shapes the impact of concurrent and future stressors (27), with comparable findings in humans whereby previous exposure to controllable stressors facilitates stress regulation (40). Such stress-regulating effects have been attributed to the increases in control beliefs (27), with subjective control beliefs shown to buffer against future stressors in humans (41) and internalising symptoms (36). Control also calibrates goal-directed exploration, which is fostered when opportunities for obtaining desirable outcomes seem achievable (25, 42). The impact of controllable stress on exploration has been amply demonstrated in animals (43–45) with such effects even persisting across developmental stages, such that exposure to uncontrollable stress in adolescence predicts reduced exploration in adulthood (45). In humans, infants exposed to contingent reinforcement displayed more exploratory behaviour (indexed by reaching for novel objects; 47), whilst in adults, self-reported control beliefs are positively associated with task-based exploration (47). Finally, high self-reported control beliefs and positive performance feedback (an established social control-related cue; 48, 49) are associated with greater perception of opportunity under uncertainty, leading to more risk-taking behaviour (50).

Early life adversity is known to also impact goal-directed exploration and stress responses. Indeed, previous institutionalisation, maltreatment or exposure to violence in childhood leads to a cascade of adverse physiological and affective consequences, including altered amygdala reactivity in response to affective stimuli (20, 51–54), increased skin-conductance response to fear-associated stimuli (55), heightened stress-reactivity (56, 57), and reduced stress-regulation (58, 59). Likewise, in children, early life unpredictability, maltreatment, and previous institutionalisation are associated with reductions in exploratory behaviour as operationalised via reinforcement learning or self-report measures (60–63), and crucially, such effects can endure into adulthood (64, 65). Here we bring together previously distinct strands of research to examine how experiences of maltreatment impact the degree to which control beliefs shape stress responses and goal-directed exploration.

To address these questions, we used a novel experimental task, with excellent psychometric properties, that allowed both measuring and manipulating control beliefs (41). In a large sample of adults (N = 477) with and without a self-reported history of childhood maltreatment, we manipulated task controllability (high vs low) and social control-related cues via performance feedback (relative positive vs relative negative; (49), leading to 8 groups. We measured task performance, control beliefs, stress and exploration throughout the task, and in doing so, were able to probe how maltreatment shapes the calibration of control beliefs and a sensitivity to control manipulations in terms of stress regulation and goal-directed exploration.

Method

Participants

We performed a power calculation based on expected effect sizes for three-way interactions on control beliefs with the same experimental design using linear models, from pilot data (f = 0.185). The estimated target sample size was 427 divided across 8 groups (approximately 53 participants per group). We oversampled to compensate for participant exclusion and data loss. Participants were recruited using the online recruitment platform, Prolific (www.prolific.com); a platform previously used for studying early adversity (38, 66). To be included in the main study participants must have been between 18 and 40 years old and currently residing in the UK (however, one participant residing in Spain also took part despite Prolific study filters).

Participants were excluded given the presence of diagnosed intellectual disability, or neurodevelopmental or psychotic disorders. Participants were pre-screened with the 28-item version of the Childhood Trauma Questionnaire (CTQ-SF; 68) and demographic questions including age, sex, gender, self-reported psychiatric diagnoses and socioeconomic status (SES; indexed by level of education on a score from 1, lowest, to 5, highest as shown in table S1). We screened 1395 ultimately leading to a final sample of 477 (Figure 1) split across the 8 groups (see table S2 for group sample sizes and text S1 for maltreatment grouping criteria). Maltreated and control groups were matched on SES, age and gender at the group level. See table 1 for full sample characteristics.

Table 1. Sample Characteristics

	Maltreated (n= 230)	Control (n = 247)	Group Comparison
Age: mean(SD)	31.8(5.6)	31.1(6.1)	t = -1.30, p = .194
Sex			χ^2= 0.000068, p =.993
Male: %	47.8	47.4	
Female: %	52.2	52.6	
Gender			p = .944 §
Male: %	47.0	47.0	
Female: %	51.7	52.2	
Nonbinary: %	0.9	0.8	
Other: %	0.4	0.0	
SES: mean(SD)	3.7(0.9)	3.8(0.9)	t = 0.57, p = .572
Ethnicity			χ^2= 30.93, p < .001
Asian: %	17.8	5.7	
Black: %	8.3	2.4	
Multiple ethnic groups: %	5.2	2.8	
White: %	68.7	89.1	
Relationship status			p = .159 §
Single: %	34.3	27.5	
In a relationship: %	37.0	39.7	
Married or in civil partnership: %	27.8	32.8	
Other: %	1.0	0.0	
Parenting Status: % Yes	32.6	34.8	χ^2 = 0.17, p = .680
Psychotherapy (any): % Yes	7.4	2.8	χ^2 = 4.27, p = .038
Psychiatric medication†: % Yes	20.4	16.2	χ^2= 1.17, p = .280
Diagnoses (any)‡: % Yes	18.3	8.9	χ^2= 8.29, p = .004
Childhood maltreatment: mean(SD)	60.7(12.2)	29.8(4.1)	t = -36.61, p < .001
Depression: mean(SD)	10.2(5.9)	6.5(5.0)	t = -7.41, p < .001
Generalised anxiety: mean(SD)	8.6(5.1)	5.7(4.9)	t = -6.18, p < .001
PTSD: mean(SD)	27.6(17.0)	15.8(14.9)	t = -8.03, p < .001

† Medication usage includes antidepressants, anxiolytics, antipsychotics and mood stabilisers.

‡ One participant was removed due to selecting both “other” and “none” options to the presence of psychiatric diagnoses. Diagnoses include: Anxiety disorders, depression, post-natal depression, personality disorders, OCD, PTSD, complex PTSD, body dysmorphic disorder, eating disorders, dyslexia, dyspraxia.

§ Fisher’s exact test was used where expected cell counts are less than five.

Ethics

Participants were informed that they could withdraw at any time and gave their informed consent to participate. Participants were given information on support services and were able to contact the researcher for advice regarding additional sources of support. Ethical approval was granted by UCL ethics committee (project ID number: 23349/001).

Design and Procedure

The current study made use of data as part of a larger study investigating the effects of maltreatment on control, stress, social functioning and mental health (see text S2 for study measures). Here we used a 2 (maltreated vs control), by 2 (high control vs low task controllability) by 2 (relative positive vs relative negative feedback) between-subjects factorial design. Participants were instructed to complete the tasks on a computer. We first pre-screened participants before allocating to experimental groups. Participants then completed more demographic questions and a questionnaire battery including locus of control (LoC) and baseline exploration. Participants then performed the WS task, before completing the post-task exploration measure and subsequent battery of measures with an attention check question. This was followed by a debrief, whereby participants were informed of the true nature of the study and that the feedback was fictitious. Each WS task condition was collected sequentially. Across all participants the median time taken to complete the overall study was 32 minutes and 26 seconds.

Materials

Software

Pre-screening was conducted using Qualtrics (https://www.qualtrics.com). The main study measures were programmed using Gorilla (71) and Javascript and HTML using jspsych plugins (version 6.1.0; 72) and hosted on firebase (firebase.google.com).

Measures

Mental health

We used three widely used, self-report measures to capture symptoms of depression, generalised anxiety and PTSD: the Patient Health Questionnaire (PHQ-9; 73), Generalised Anxiety Disorder 7-item scale (GAD-7; 74), and Posttraumatic Stress Disorder Checklist for DSM-5 (PCL-5; 75). The PHQ is a 9-item questionnaire on which participants rate the regularity of depression symptoms (e.g. “feeling down, depressed or hopeless”) on a scale from 0 (“not at all”) to 3 (“nearly every day”). The GAD-7 is a 7-item questionnaire on which participants rate the regulatory of anxiety symptoms (“being afraid as if something awful might happen”), on a scale from 0 (“not at all”), to 3 (“nearly every day”). The PCL-5 is a 20-item questionnaire on which participants rate how affected they are by PTSD symptoms (“having strong negative beliefs about yourself, other people or the world”) on a scale from 0 (“not at all”) to 4 (“extremely”). The PHQ-9, GAD-7, and PCL-5 summed to form total sores of depression, anxiety and PTSD respectively. The internal consistency in the current sample for PHQ-9, GAD-7 and PCL-5 with Cronbach’s alpha values of 0.88, 0.90 and 0.95, respectively.

Childhood maltreatment

Childhood maltreatment was measured using the short form of the Childhood Trauma Questionnaire (CTQ-SF; 68); a widely used retrospective self-report measure with 28 items. Five items cover each of the maltreatment types: emotional abuse (e.g. “someone in my family hated me”), physical abuse (e.g. “I got hit badly and it was noticed by a teacher, neighbour and/or doctor”), sexual abuse (e.g. “Someone tried to touch me in a sexual way or tried to make me touch them”), emotional neglect (e.g. “Felt loved”, reverse scored), and physical neglect (e.g. “I had to wear dirty clothes”), and three items capture minimisation or denial (e.g. “I had a perfect childhood”). Participants responded on a scale of 1 (never true) to 5 (very often true). The five items within each maltreatment type can then be summed to determine maltreatment severity across four categories: “None”, “Low-Moderate”, “Moderate-Severe”, or" Severe-Extreme”. The CTQ-SF displays good criterion, convergent and discriminative validity (68) and subjective, retrospective measures, compared to objective measures, of maltreatment are shown to more closely relate to psychosocial disadvantage and mental health problems (74, 75). The 25 maltreatment items displayed excellent internal consistency in the current sample (α = 0.95).

Internal and External Locus of Control

To measure internal and external LoC, we used the Internal-External Locus of Control Short Scale-4 (76); a 4-item self-report scale previously used in mental health research (77–79). The scale comprises two subscales: internal LoC (e.g. "If I work hard, I will succeed"), and external LoC (e.g. "Fate often gets in the way of my plans"). Participants respond on a 5-point rating scale from 1 ("does not apply at all" to 5 ("applies completely"). Items are summed to compute separate internal and external LoC scores. The scale demonstrates good test-retest reliability and internal and external validity (76). The internal consistency in the current sample was low for internal ($\alpha = 0.34$) and moderate for external ($\alpha = 0.51$) LoC subscales, possibly due to the small number of items (80).

Goal-directed exploration

We created a novel self-report questionnaire to measure "real-world" goal-directed exploration, consisting of 20 items on a binary scale (yes vs no) aimed to capture the propensity to try new experiences. Participants were asked "In the next month, which, if any, of the following activities might you try?". To maximise clinical applicability, item selection was inspired by activity catalogues used in behavioural activation, an evidence-based treatment for mood disorders (81). Items spanned social domains (10 items, e.g. "Attend a social event (e.g. a party) that you would not usually attend") and non-social domains (10 items, e.g. "Learn a new skill"). See table S3 for full list of items. Selected items were summed, leading to a total score ranging from 0 to 20. The measure displayed good internal consistency before ($\alpha = 0.76$) and after ($\alpha = 0.78$) the WS task.

Wheel Stopping task

Stimuli*.* To measure control beliefs and stress, we used the Wheel Stopping (WS) task (41, 49). During this task participants are presented with a blue spinning wheel with a yellow segment and a designated brake zone (red bar; figure 1). Participants must deploy carefully orchestrated actions to stop the yellow segment on the designated brake zone, using the brake button ('b'). Three parameters of the spinning wheel were manipulated, previously shown to track moment-to-moment fluctuations in control beliefs (41): wheel speed, deceleration and segment size. Each parameter had 4 levels of difficulty (with the exception of segment size which only had

3 levels in the low controllability groups), and combinations of each parameter were repeated within blocks of five trials but varied across blocks. The order of parameter combinations between blocks were randomly presented within each participant.

Controllability and feedback manipulations. We manipulated two separate sources of information indicating environmental controllability previously shown to impact control beliefs in the WS task (41, 49): task controllability and relative performance feedback. Whilst the WS task is objectively controllable, the degree of controllability varied as a function of the controllability manipulation (high vs low). In the high control groups, the wheel stops after one brake press, whereas in the low control groups, the brake must be pressed multiple times before eventually stopping. In the low control group, each brake press incrementally increases the brake strength, with greater strengths stopping the wheel more quickly. For details on how deceleration was calculated within the high and low control conditions, see Fielder and colleagues (41). The low control groups also had, on average larger segment sizes (split across 3 levels), and faster wheel speeds.

The feedback manipulation involved presenting participants with fictitious feedback concerning their relative performance. Prior to beginning the WS task, participants were informed that an algorithm was used to cumulatively calculate their performance relative to over 2000 other participants taking part in the study, in the form of a percentage (figure 1). To increase plausibility, participants were informed that the algorithm considers information on their performance until that point, including the number of wins they obtained, final proximity to the break zone, and other information that was not disclosed. Feedback was presented every 5 trials, before the slider rating scale. Feedback percentages in the high feedback groups ranged from the top 35% to the top 10%, whereas in the low feedback groups, ranged from the bottom 35% to bottom 10%. The specific percentages within those boundaries were presented in a random order for each participant.

Slider scales. Every block of 5 trials, participants were presented with self-report rating scales, on a scale of 0 to 100 (numeric values were not presented to participants; figure 1). One measuring control beliefs: “How in control do you feel right now?” from “very out of control” to “very in control”. Another capturing perceived task difficulty: “How difficult are you finding the task right now?” from “not at all difficult” to "very difficult". A final rating scale was used to capture subjective stress levels: "How much stress are you currently experiencing?" from "very little stress" to "a lot of stress".

Wheel Stopping task procedure. Participants were first presented with a baseline stress slider, followed by the WS task instructions. Before beginning the WS task, participants were informed that they were given a £3 bonus at the beginning of the experiment, but that, at the end of the task, one trial would be selected from the WS task which would define whether they kept the bonus (41). If they won on that trial, they would keep their bonus, but not if they lost. As potential losses have been shown to be aversive (82, 83), such an approach was used to motivate participants and has been successfully implemented in previous versions of the WS task (41). Next, participants were informed that they would receive feedback on their performance, as calculated by the algorithm. Participants were then given 5 practice trials. After each trial, participants were presented with a screen informing them: "if this trial had been chosen you would have [kept/lost] your bonus!", depending on whether they won or lost that trial. Participants then completed 5 baseline trials of the WS task and a control rating scale, to capture baseline control beliefs before the feedback manipulation was introduced. Participants then began the Wheel Stopping task, where they played five trials, followed by feedback and a rating scale. Control and difficulty rating scales were presented alternately every 5 trials. Participants began with a control rating scale. The stress rating scales were presented periodically alongside control or difficulty rating scales, after trials 30, 55, 80 and 100. The task proper consisted of 100 trials, and therefore participants had a total of 10 difficulty ratings, 10 control ratings (and one baseline) and 4 stress ratings (and one baseline). Participants were given the opportunity to take a short break after trial 55. After completion, participants were informed of the outcome of the random trial selection and therefore whether they kept or lost their bonus.

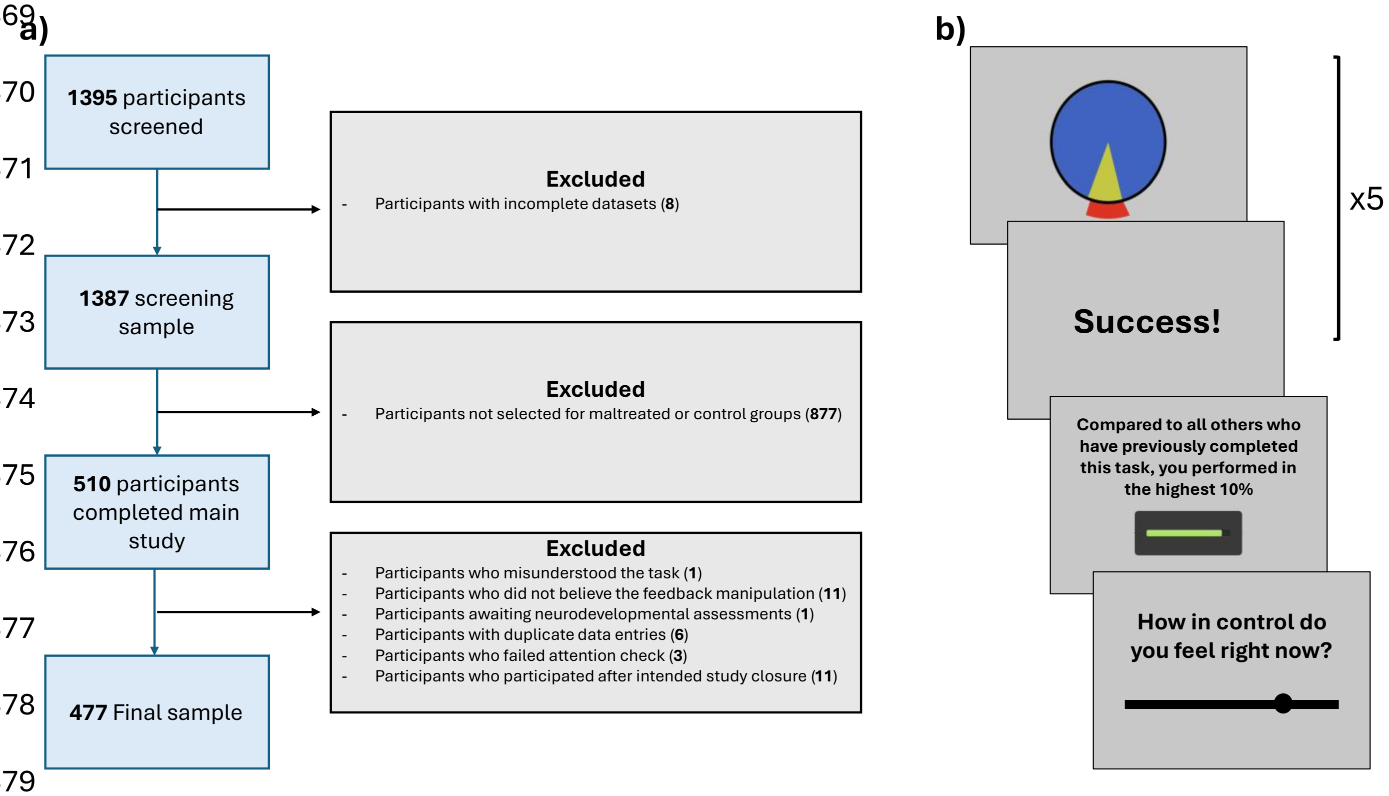

Figure 1. a) Participant exclusion strategy from screening to final sample. b) Visual depiction of the WS task procedure with the high feedback condition used as the example. Control and difficulty rating scales alternated every 5 trials. Stress rating scales appeared periodically in addition to control or difficulty rating scales. Panel b) adapted from Fielder and colleagues (41).

Data Analysis

Data processing was conducted in the statistical software, MATLAB (84) and R (85) and all formal analysis was conducted in R. Linear mixed effects models were built using the R packages “lme4” (86) and “lmerTest” (87) and estimated with Restricted Maximum Likelihood (REML) estimations. Simple slopes were estimated for post-hoc analyses using the “emtrends” function within the R package, “emmeans” (88), and FDR-corrected for multiple comparisons. Pairwise contrasts were then conducted using the “pairs” function from the “emmeans” package, with FDR-corrected p values. When using linear mixed effects models, we report full model statistics for all effects including beta coefficients, standard errors, t statistics, degrees of freedom, p values, intraclass correlation coefficients, random effects residuals, participant random intercepts and conditional and marginal R^2 values in tables S4-S9. In all linear models, Group (maltreated vs control), Controllability (high vs low) and Feedback (relative positive vs relative negative) were set as binary factors. In linear mixed effects models, Timepoint was also included as a continuous fixed effect based on the number of responses for that variable (win percentage: 1-20; control beliefs: 1-10; stress: 1-4, exploration: pre-post), along with all interactions among fixed effects and participant as a random intercept. In all linear models and the reference values for the categorical factors were set to the default levels of control Group, relative positive Feedback, and high Controllability.

We first present baseline differences across maltreated and control participants in internal LoC, external LoC, stress and goal-directed exploration using independent samples t tests, applying FDR-correction for four comparisons. We next examined the associations between mean control beliefs (calculated using all responses, including baseline) and mental health using linear regression models in maltreated and control groups separately, applying FDR-corrections for six models. To discern if any differences in subjective experiences could be confounded by differential task performance, we explored overall levels of, and change in, performance as operationalised by win percentage (the percentage of successful trials in blocks of 5 trials), using linear mixed effects models. Crucially, we then examined group differences in change in control beliefs also using linear mixed effects models. Further, we tested whether maltreatment impacted how task performance is used to update control beliefs by conducting within-subjects regression models, predicting trial-by-trial control beliefs by win percentages whilst covarying for speed, deceleration and segment size. Win percentages were calculated as percentages of successful trials within blocks of five trials preceding a control rating scale, excluding the baseline trials (10 blocks). We then extracted the weights corresponding to win percentages (hereafter, win weights), and performed multiple linear regression predicting win weights from Group whilst covarying for Controllability and Feedback manipulations. Finally, linear mixed effects models were used to examine group differences in change in stress and exploration throughout the task. Given that each linear mixed effect model addresses independent research questions, we did not correct for multiple comparisons (89–91).

Results

Baseline group differences

Independent samples t tests were conducted to compare groups on baseline measures of internal LoC, external LoC, stress and goal-directed exploration (figure S1). Compared to the controls, the maltreated group displayed significantly lower baseline internal LoC (Maltreated: mean = 3.1, SD = 0.9; Controls: mean = 3.2, SD = 0.8; $t(475) = 1.98$, $p = .048$, $p_{adj} = .048$, $d = 0.18$), higher external LoC (Maltreated: mean = 2.6, SD = 0.8; Controls: mean = 2.3, SD = 0.7; $t(475) = -3.95$, $p < .001$, $p_{adj} < .001$, $d = -0.36$), higher baseline levels of stress (Maltreated: mean = 55.0, SD = 27.1; Controls: mean = 42.0, SD = 26.8; $t(475) = -5.26$, $p < .001$, $p_{adj} < .001$, $d = -0.48$), and lower goal-directed exploration (Maltreated mean = 7.0, SD = 3.7; Controls: mean = 7.8, SD = 3.6; $t(475) = 2.50$, $p = .013$, $p_{adj} = .017$, $d = 0.23$)

Control beliefs and mental health

Multiple regression was used to examine the relations between mean control beliefs and symptoms of anxiety, depression, and PTSD, whilst controlling for Controllability and Feedback (figure S2). Mean control beliefs were negatively associated with anxiety in both groups (Maltreated: $B = -0.06$, $t(226) = -3.76$, $p < .001$, $p_{adj} < .001$; Control: $B = -0.05$, $t(243) = -2.94$, $p = .004$, $p_{adj} = .007$). Mean control beliefs were marginally negatively associated with depression symptoms in both groups (maltreated: $B = -0.04$, $t(226) = -1.94$, $p = .054$, $p_{adj} = .067$; control: $B = -0.03$, $t(243) = -1.92$, $p = .056$, $p_{adj} = .067$). Mean control beliefs were negatively associated with PTSD symptoms in the maltreated group ($B = -0.23$, $t(226) = -4.04$, $p < .001$, $p_{adj} < .001$ but not the control group ($B = -0.07$, $t(243) = -1.45$, $p = .148$, $p_{adj} = .148$).

Task performance

We detected a main effect of Timepoint ($B = 0.69$, SE = 0.13, $t(9055) = 5.32$, $p < .001$, semi-partial $R^2 = 0.0049$) and Controllability ($B = -9.26$, SE = 2.75, $t(1337) = -3.37$, $p = .001$, semi-partial $R^2 = 0.0644$) and a Controllability by Timepoint interaction ($B = -0.47$, SE = 0.17, $t(9055) = -2.77$, $p = .006$, semi-partial $R^2 = 0.0012$). Post hoc simple slopes revealed that the effect of Timepoint was significant in both Controllability conditions (low: $B = 0.19$, SE = 0.06, $p = .002$, $p_{adj} =.002$; high: $B = 0.51$, SE = 0.06, $p < .001$, $p_{adj} < .001$). Importantly, pairwise contrasts on these simple slopes indicate that the effect was significantly larger in the high Controllability group, $B = 0.33$, SE = 0.09, $t(9055) = 3.76$, $p < .001$, suggesting that the high Controllability group displayed significantly greater increases in win percentage compared to the low

Controllability group (figure 2). No other effects reached statistical significance (table S4).

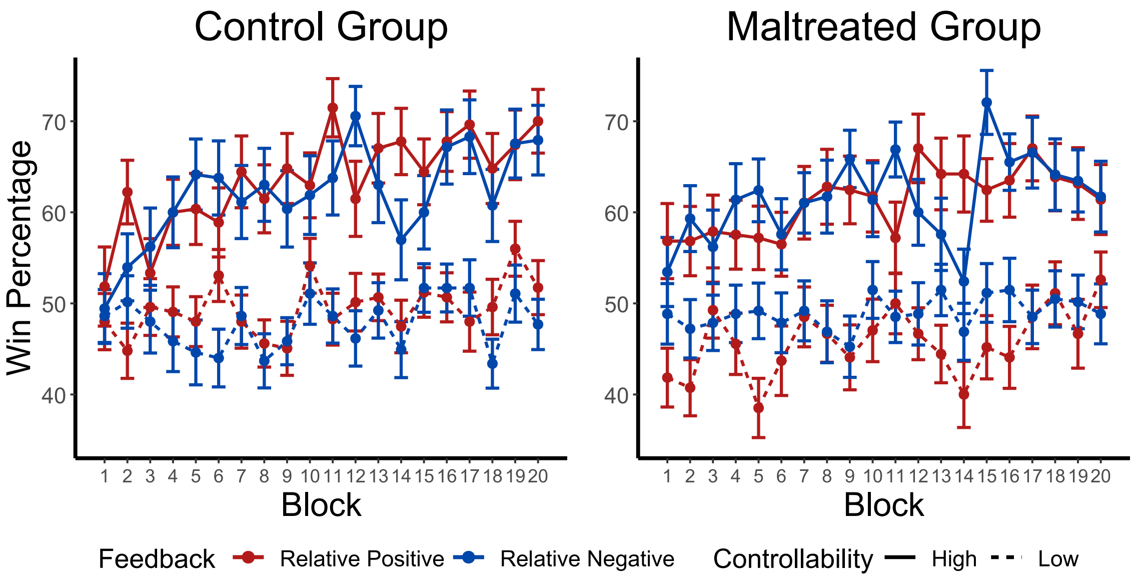

Figure 2. Percentage of wins per block of five trials across the task within maltreated and control groups. Practice and baseline trials are excluded from plot. Points and error bars represent means and standard error of the mean respectively.

Control beliefs

A significant main effect of Timepoint emerged (*B* = 0.66, SE = 0.22, *t*(4285) = -3.04, *p* = 0.002, semi-partial R^2 = 0.0004) such that control beliefs increased over time. Additionally, a significant Controllability by Timepoint interaction was detected (*B* = -0.73, SE = 0.28, *t*(4285) = -2.57, *p* = 0.010, semi-partial R^2 = 0.0006). Post hoc analyses with estimated marginal trends revealed that, while the effect of Timepoint reached statistical significance in the high Controllability group, *B* = 0.43, SE = 0.11, $p < .001$, $p_{adj} < .001$, the effect did not reach significance in the low Controllability group, *B* = -0.03, SE = 0.10, *p* = .738, p_{adj} = .738. Pairwise contrasts on these simple slopes, indicate that the effect was significantly larger in the high controllability group, *B* = 0.46, SE = 0.15, *t*(4285) = 3.15, *p* = .002. Crucially, there was also a significant Group by Timepoint interaction (*B* = -0.66, SE = 0.30, *t*(4285) = -2.19, *p* = .029, semi-partial R^2 = 0.0004) with post hoc simple slopes revealing that the effect was significant for controls (*B* = 0.41, SE = 0.10, $p < .001$, $p_{adj} < .001$) but not the maltreated group (*B* = -0.01, SE = 0.11, *p* = .888, p_{adj} = .888). Importantly, pairwise contrasts on these simple slopes indicate that the effect was significantly larger in the control group, *B* =

0.43, SE = 0.15, *t*(4285) = 2.90, *p* = .004, suggesting that the maltreated group are less able to increase their control beliefs over time (figure 3). No other interactions involving maltreatment and timepoint reached statistical significance (table S5).

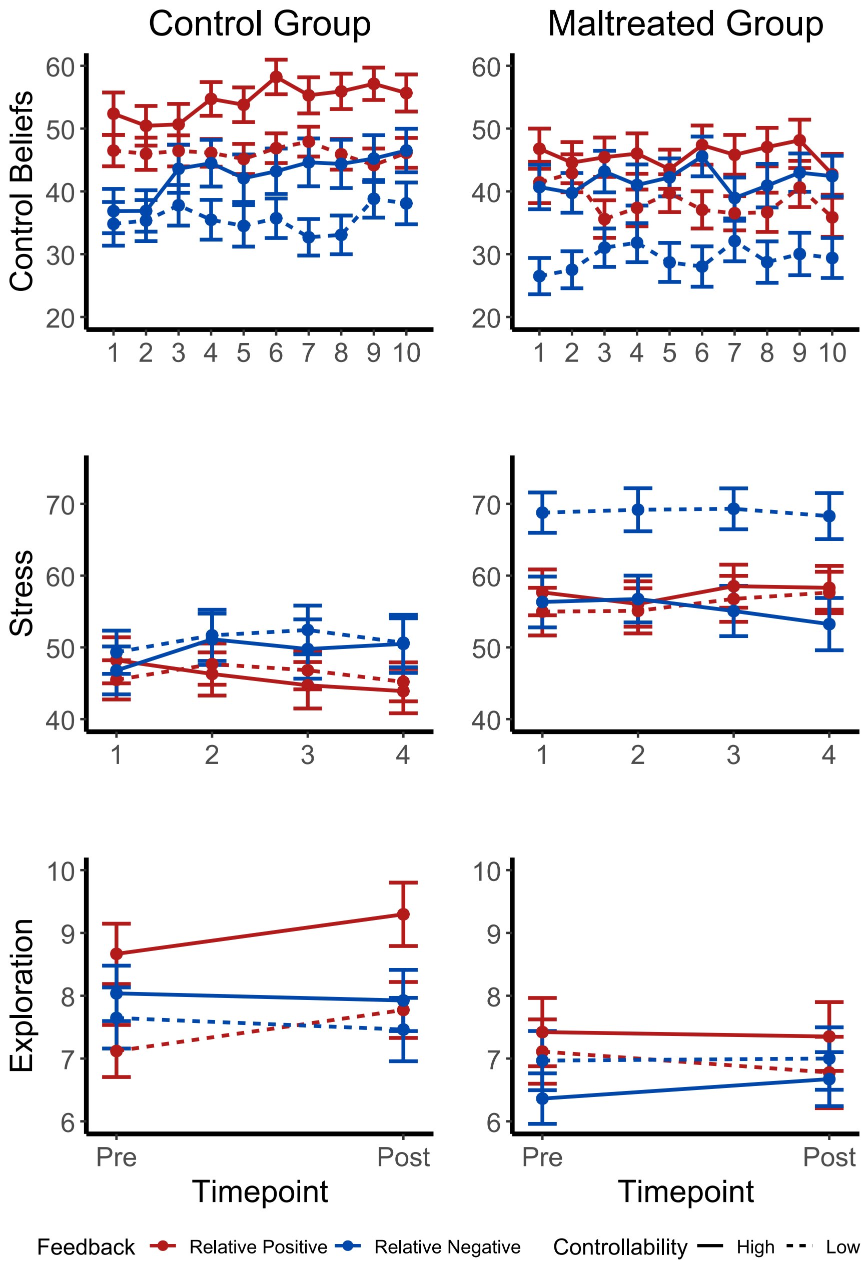

Figure 3. Control beliefs, stress, and exploration within maltreated and control groups. Baseline control beliefs and stress are excluded from plot. Points and error bars represent means and standard error of the mean respectively.

Win weights

Multiple regression was used to examine the association between Group (maltreated vs control) and win weights, whilst covarying for Controllability and Feedback manipulations. We detected a marginal negative effect of Group on win weights (B = -0.05, t(473) = -1.74, p = .082) providing tentative evidence that maltreated individuals use task performance less when updating control beliefs (figure 4).

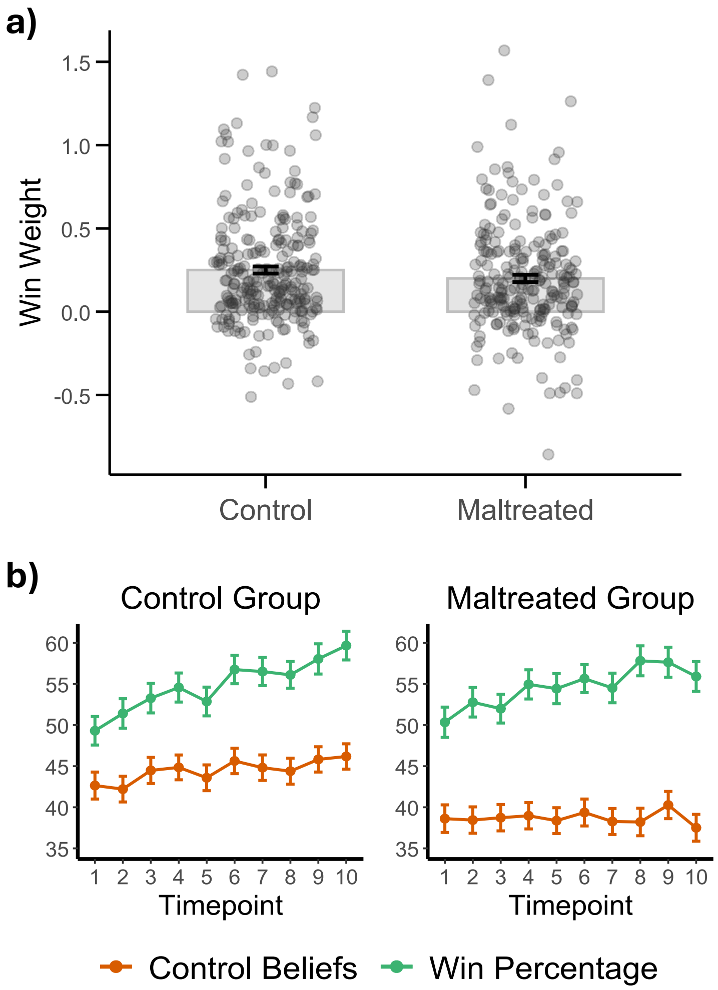

Figure 4. a) Mean win weights across maltreated and control groups. Points represent individual data points. Bars and error bars represent mean and standard error of the mean, respectively. b) Percentage of wins per block of five trials immediately preceding control rating scale (green), and control beliefs (orange). Baseline trials are excluded from plot. Points and error bars represent mean and standard error of the mean respectively.

Stress

We detected a significant effect of Timepoint (β = -1.45, SE = 0.64, $t(1423) = -2.26$, $p = .024$, semi-partial $R^2 < 0.0001$), a Feedback by Timepoint interaction (β = 2.42, SE = 0.91, $t(1423) = 2.67$, $p = .008$, semi-partial $R^2 < 0.0001$) and a Group by Timepoint interaction (β = 1.88, SE = 0.89, $t(1423) = 2.11$, $p = .035$, semi-partial $R^2 < 0.0001$). Importantly, we also detected triple interaction between Group, Feedback and Timepoint (β = -3.95, SE = 1.26, $t(1423) = -3.13$**,** $p = .002$, semi-partial $R^2 = 0.009$). No post hoc estimated marginal trends reached significance after FDR-correction (table S6), yet crucially, pairwise contrasts revealed that, in the relative negative Feedback condition, there was only a trending difference between maltreated and control Groups, β = 1.33, SE = 0.61, $t(1423) = 2.18$, $p = .029$, $p_{adj} = .052$, yet in the relative positive feedback condition, the control group displayed significantly more negative simple slopes of Timepoint, β = -1.51, SE = 0.61, $t(1423) = -2.47$, $p = .014$, $p_{adj} = .041$. These findings thus suggest that the maltreated group was less able to leverage the relative positive feedback to reduce their stress over time (figure 3). No other interactions reached statistical significance (table S7).

Goal-directed exploration

We detected a main effect of Timepoint (β = 0.63, SE = 0.29, $t(469) = 2.20$, $p = .029$, semi-partial $R^2 = 0.0003$) and a significant triple interaction between Group, Feedback and Timepoint (β = 1.12, SE = 0.57, $t(469) = 1.99$, $p = 0.048$, semi-partial $R^2 = 0.0015$). Post hoc analysis of simple slopes revealed that the control Group receiving relative positive Feedback showed a significant increase in goal-directed exploration over time (β = 0.64, SE = 0.19, $p < .001$). No other simple slopes reached statistical significance (table S8). Crucially, pairwise contrasts indicate no significant differences in simple slopes of Timepoint between control and maltreated groups in the relative negative feedback condition, β = -0.32, SE = 0.27, $t(469) = -1.17$, $p = .243$, $p_{adj} = .292$, yet in the relative positive feedback condition, the control group displayed significantly greater simple slopes of Timepoint, β = 0.84, SE = 0.27, $t(469) = 3.07$, $p = .002$, $p_{adj} = .011$. These findings suggest that the maltreated group was less able to leverage the relative positive feedback to promote goal-directed exploration (figure 3). No other interactions reached statistical significance (table S9).

Discussion

Childhood maltreatment can profoundly impact neurocognitive systems heightening the risk for later psychopathology (10, 11, 13–16, 51, 53, 92). Here we systematically examined how childhood maltreatment affects individuals' control beliefs and whether maltreatment is related to a differential sensitivity to manipulations of control beliefs (relative performance feedback and task controllability) on stress responses and goal-directed exploration. We present two core findings. Firstly, while performance improved over time similarly for both groups, the control group appeared more able to use this to update their control beliefs. Secondly, whereas both groups displayed similar overall responses to task manipulations, only controls leveraged relative positive feedback to reduce task-related stress and increase goal-directed exploration. Our findings suggest that control beliefs play a pivotal role in the impact of maltreatment on stress and exploration, highlighting this as a potential mechanism for latent vulnerability to mental health problems following maltreatment.

At baseline, compared to controls the maltreated group displayed reduced internal locus of control and increased external locus of control, consistent with prior literature (36, 38, 39). Such altered control beliefs are a likely consequence of formative developmental experiences where control has been drastically undermined. Our sample of individuals with maltreatment experience also displayed higher levels of stress at baseline, consistent with empirical literature finding increased stress reactivity (55–57), and reduced stress regulation (54, 58) in maltreated adults. Finally, consistent with prior literature (60, 61), we find that the maltreated group display reduced goal-directed exploration at baseline compared to control participants. This may represent an adaptive response to maltreating environments where rewards are both scarce and unpredictable (93), but in turn compromise learning and discovery of new resources in normative environments.

Compared to controls, individuals with a history of maltreatment displayed a reduced ability to update their control beliefs, despite displaying comparable improvements in objective task performance. This may reflect a heightened precision-weighting (perceived confidence) assigned to prior beliefs (previously held assumptions about the world), or a reduced precision-weighting on contradictory evidence, in turn rendering beliefs less malleable in the face of disconfirming information. Increased precision-weighting on prior beliefs may reflect an adaptation to environments characterised by consistent parental insensitivity (94) or maltreatment. That is, the *consistent* lack of control experienced in maltreating environments may lead to not only reduced beliefs of control but increased *confidence* in those beliefs, rendering them more resistant to change. Here, when probing the trial-by-trial relationship between task performance and control beliefs, we derived trending evidence that the maltreated group actually under-weight experiences of success when updating their control beliefs. Computational approaches could offer useful insights into whether the maltreatment-related deficits in control belief updating are due to increased precision-weighting on prior beliefs, reduced precision-weighting on contradictory evidence, or both.

The current findings build on previous literature suggesting that controllability manipulations impact stress and exploration (40, 41, 46, 95, 96). We show that relative positive feedback reduces stress and increases goal-directed exploration significantly more in the controls than maltreated individuals. In other words, maltreated individuals may be less able to benefit from the stress-regulating and exploration-promoting effects of social control-related cues. We suggest that these findings reflect a general imperviousness to positive feedback, possibly reflecting “cognitive immunisation” (97) whereby, incoming information is discounted or reappraised, thereby weakening the degree to which it is internalised. Here, maltreated individuals may reappraise the positive feedback in terms of its credulity (i.e. “the feedback algorithm is not correct”) or attribute it to an external factor (“I was just lucky”), as has been detected in maltreatment-related disorders such as depression (97, 98). Such cognitive biases may contribute to a reduced ability to build and maintain social architecture (11) and a poorer ability to make use of their social environment to build resilience (99). We speculate that this reduced ability to use social control-related cues may lead to elevated and sustained levels of stress, contributing to an increase in allostatic load (100, 101). Alongside, it may reduce the tendency to explore novel options, undermining the capacity to uncover unexpectantly rewarding or supportive environments. This twin impact may contribute to the emergence of mental health problems over time.

The current findings have potential implications for clinical practice. Overarchingly, it is clear that maltreatment impacts the ability to use social control-related cues to adaptively inform stress responses and exploration. Empirically, it would be important to establish how changing the processing of such cues could be leveraged within the context of preventative or clinical interventions. Example interventions might include those with shown effectiveness at modifying unhelpful interpretations of events, such as cognitive restructuring (102). We speculate that such interventions may help maltreated individuals adaptively use positive social control-related cues to regulate stress and promote exploration.

This study investigated the impact of maltreatment on the calibration of control beliefs. Individuals with a history of maltreatment display reduced locus of control, increased stress and reduced goal-directed exploration. Moreover, we find pervasive impairments in both control belief updating and the ability to leverage social control-related cues to regulate stress and guide exploration. We propose this profile reflects a marker of latent vulnerability, likely contributing to the significant mental health difficulties of individuals with a history of childhood maltreatment.

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Supporting Information

Table S1

Socioeconomic status scoring

Score	Education level
1	No formal qualifications (e.g. primary school)
2	GCSEs, O-levels, NVQ levels 1 & 2
3	A-level, AS-levels, NVQ level 3, BTEC diplomas
4	Undergraduate degree (BSc, BA) or equivalent (HND/HNC, City and Guilds Qualification, NVQ level 4)
5	Postgraduate degree (MSc, MA, PhD) or professional qualification (e.g. law or accountancy training)

Table S2

Group sample sizes

Group	Maltreated	Control
Controllability[High], Feedback[Relative Positive]	57	54
Controllability[Low], Feedback[Relative Positive],	58	53
Controllability[High], Feedback[Relative Negative],	54	75
Controllability[Low], Feedback[Relative Negative],	61	65

Text S1

Maltreatment grouping criteria

For the maltreated group, participants were required to have experienced abuse or neglect (i.e. at least at the level of the "Moderate-Severe" threshold previously established by the CTQ manual) on at least **two** maltreatment domains (emotional abuse ≥ 13, physical abuse ≥ 10, sexual abuse ≥ 8, emotional neglect ≥ 15 and physical neglect ≥ 10), a marginally higher threshold than previous studies (1, 2). The control group was required to score below the "Moderate-Severe" threshold on **all** maltreatment domains, consistent with previous studies (2).

Text S2

Study measures

1. WS Task (3, 4)
2. Exploration Questionnaire
3. Internal-External Locus of Control Short Scale-4 (5)
4. WS Task Attribution Question
5. Patient Health Questionnaire (6)
6. Generalised Anxiety Disorder 7-item scale (7)
7. Posttraumatic Stress Disorder Checklist for DSM-5 (8)
8. Social Readjustment Rating Scale (9)
9. Circumplex Scale of Interpersonal Problems (10)
10. Face trust task (11, 12)
11. Childhood Trauma Questionnaire Short-Form (13)
12. Three-Item Loneliness Scale (14)
13. UK Biobank Isolation (15)

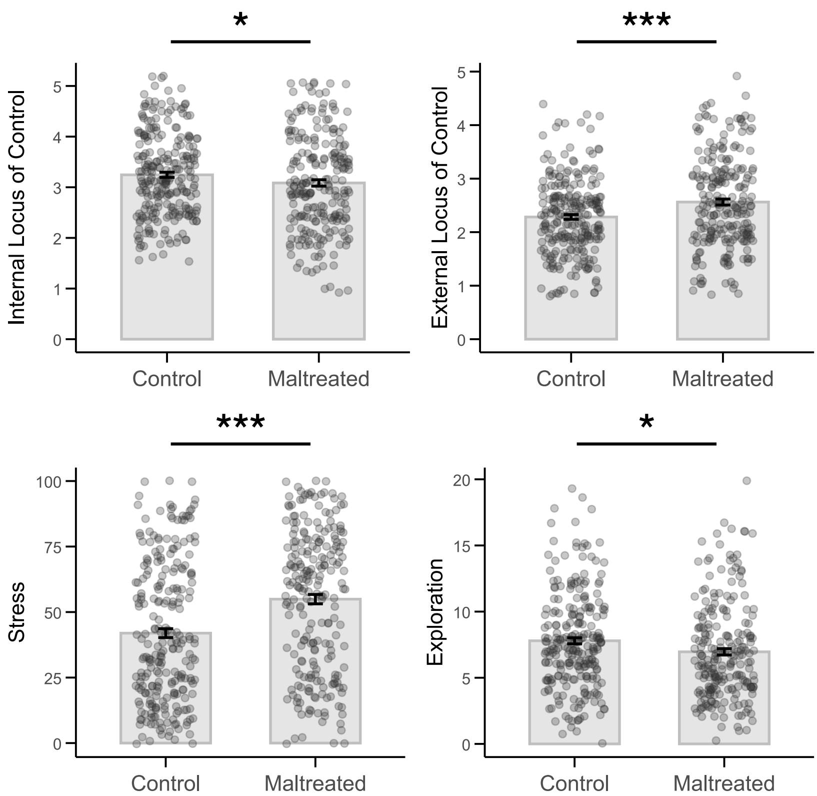
Supporting Table S3

Exploration propensity items

Domain	Item
Social	Organise a social event (e.g. dinner party) that you would not usually organise
Social	Arrange to meet a friend in a new context (e.g. bar or coffee shop)
Social	Attend a social event (e.g. a party) that you would not usually attend
Social	Make new friends/meet new people
Social	Join a dating website or app
Social	Go to eat at a new restaurant with a friend
Social	Enrol in a new class (e.g. online course, evening class etc)
Social	Try a random act of kindness
Social	Play a new team sport
Social	Join a new group
Non-social	Learn a new skill
Non-social	Read a new book
Non-social	Try a new activity
Non-social	Find some new music to listen to
Non-social	Attend a live event (i.e. music, comedy, theatre, sports) that you would not usually attend
Non-social	Watch a new film or TV show
Non-social	Go to a new art gallery, exhibition or museum
Non-social	Take a new route when going on a walk
Non-social	Try new ways to exercise
Non-social	Cook something new

Supporting Figure 1

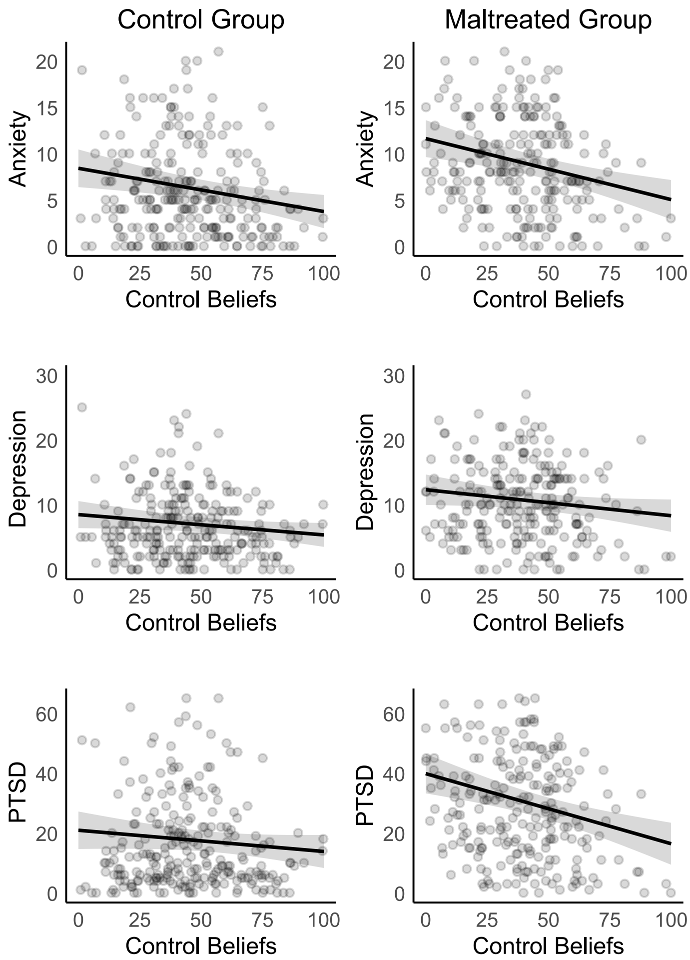
Baseline group differences in internal locus of control, external locus of control, stress, and exploration



Note. Circles represent individual data points, error bars represent standard error of the mean and * = p<.05, while *** = p<.001.

Supporting Figure 2

Scatter plot for mean control beliefs and anxiety, depression, and PTSD within maltreated and control groups.



Note. Lines represent linear regression models while covarying for Controllability and Feedback manipulations. Shaded region represents 95% confidence intervals.

Supporting Table S4

Linear mixed effects model results for change in win percentage

Predictors	**Estimates**	**SE**	***t*(DF)†**	***p***
(Intercept)	56.42	2.10	26.91(1337)	<0.001
Maltreatment [Maltreated]	0.35	2.93	0.12(1337)	0.906
Feedback [Low]	-0.42	2.98	-0.14(1337)	0.888
Controllability [Low]	-9.26	2.75	-3.37(1337)	0.001
Timepoint	0.69	0.13	5.32(9055)	<0.001
Maltreatment [Maltreated] × Feedback [Low]	1.36	4.14	0.33(1337)	0.742
Maltreatment [Maltreated] × Controllability [Low]	-4.79	4.01	-1.19(1337)	0.233
Feedback [Low] × Controllability [Low]	-0.11	3.96	-0.03(1337)	0.978
Maltreatment [Maltreated] × Timepoint	-0.26	0.18	-1.44(9055)	0.151
Feedback [Low] × Timepoint	-0.11	0.18	-0.62(9055)	0.535
Controllability [Low] × Timepoint	-0.47	0.17	-2.77(9055)	0.006
(Maltreatment [Maltreated] × Feedback [Low]) × Controllability [Low]	4.18	5.68	0.74(1337)	0.462
(Maltreatment [Maltreated] × Feedback [Low]) × Timepoint	0.05	0.25	0.20(9055)	0.841
(Maltreatment [Maltreated] × Controllability [Low]) × Timepoint	0.33	0.25	1.34(9055)	0.181

(Feedback [Low] × Controllability [Low]) × Timepoint	0.01	0.24	0.04(9055)	0.970
(Maltreatment [Maltreated] × Feedback [Low] × Controllability [Low]) × Timepoint	-0.12	0.35	-0.35(9055)	0.730
Random Effects				
σ^2	594.65			
$\tau_{00\ participant}$	109.03			
ICC	0.15			
N	477			
Observations	9540			
Marginal R^2 / Conditional R^2	0.072 / 0.216			

Note. Estimate represents unstandardised beta coefficient, SE represents standard error, t(DF) represent t value and degrees of freedom, p represents significance value, ICC represents intraclass correlation coefficient, σ^2 represents random effects residual, and $\tau_{00\ participant}$ represents participant random intercept.

†Degrees of freedom are rounded to the nearest whole number.

Supporting Table S5

Linear mixed effects model of change in control beliefs

Predictors	**Estimates**	**SE**	***t*(DF)†**	***p***
(Intercept)	50.79	2.91	17.46(675)	<0.001
Maltreatment [Maltreated]	-5.04	4.06	-1.24(675)	0.215
Feedback [Low]	-13.02	4.13	-3.15(675)	0.002
Controllability [Low]	-4.29	3.82	-1.12(675)	0.261
Timepoint	0.66	0.22	3.04(4285)	0.002
Maltreatment [Maltreated] × Feedback [Low]	8.23	5.74	1.43(675)	0.152
Maltreatment [Maltreated] × Controllability [Low]	-0.91	5.57	-0.16(675)	0.871
Feedback [Low] × Controllability [Low]	1.39	5.50	0.25(675)	0.801
Maltreatment [Maltreated] × Timepoint	-0.66	0.30	-2.19(4285)	0.029
Feedback [Low] × Timepoint	0.25	0.31	0.82(4285)	0.413
Controllability [Low] × Timepoint	-0.73	0.28	-2.57(4285)	0.010
(Maltreatment [Maltreated] × Feedback [Low]) × Controllability [Low]	-8.84	7.88	-1.12(675)	0.262
(Maltreatment [Maltreated] × Feedback [Low]) × Timepoint	-0.10	0.43	-0.24(4285)	0.809
(Maltreatment [Maltreated] × Controllability [Low]) × Timepoint	0.33	0.42	0.802(4285)	0.422
(Feedback [Low] × Controllability [Low]) × Timepoint	-0.04	0.41	-1.07(4285)	0.915

(Maltreatment [Maltreated] × Feedback [Low] × Controllability [Low]) × Timepoint	0.49	0.59	0.83(4285)	0.405
Random Effects				
σ^2	209.51			
τ_{00} Participant	359.36			
ICC	0.63			
N	477			
Observations	4770			
Marginal R^2 / Conditional R^2	0.082 / 0.662			

Note. Estimate represents unstandardised beta coefficient, SE represents standard error, t(DF) represent t value and degrees of freedom, p represents significance value, ICC represents intraclass correlation coefficient, σ^2 represents random effects residual, and τ_{00} participant represents participant random intercept.

†Degrees of freedom are rounded to the nearest whole number.

Supporting Table S6

Simple slopes of Timepoint by Group by Feedback interaction on stress

Group	Estimate	SE	*p*	p_{adj}
Group[Control], Feedback[Relative Positive]	-0.81	0.42	.054	.154
Group[Control], Feedback[Relative Negative]	0.72	0.44	.096	.154
Group[Maltreated], Feedback[Relative Positive]	0.70	0.45	.116	.154
Group[Maltreated], Feedback[Relative Negative]	-0.61	0.43	.156	.156

Note. Estimate represents unstandardised simple slope, SE represents standard error, p represents significance value, p_{adj} represents FDR-corrected p significance value.

Supporting Table S7

Linear mixed effects model of stress change

Predictors	Estimates	SE	t(DF) †	p
(Intercept)	49.40	3.52	14.04(728)	<0.001
Feedback [Low]	-2.28	5.00	-0.46(728)	0.648
Controllability [Low]	-2.68	4.61	-0.58(728)	0.561
Maltreatment [Maltreated]	7.15	4.91	1.46(728)	0.146
Timepoint	-1.45	0.64	-2.26(1423)	0.024
Feedback [Low] × Controllability [Low]	5.41	6.65	0.81(728)	0.416
Feedback [Low] × Maltreatment [Maltreated]	3.82	6.95	0.55(728)	0.583
Controllability [Low] × Maltreatment [Maltreated]	-0.16	6.74	-0.02(728)	0.982
Feedback [Low] × Timepoint	2.42	0.91	2.67(1423)	0.008
Controllability [Low] × Timepoint	1.28	0.84	1.52(1423)	0.128
Maltreatment [Maltreated] × Timepoint	1.88	0.89	2.11(1423)	0.035
(Feedback [Low] × Controllability [Low]) × Maltreatment [Maltreated]	8.57	9.53	0.90(728)	0.369
(Feedback [Low] × Controllability [Low]) × Timepoint	-1.78	1.21	-1.47(1423)	0.141
(Feedback [Low] × Maltreatment [Maltreated]) × Timepoint	-3.95	1.26	-3.13(1423)	0.002

(Controllability [Low] × Maltreatment [Maltreated]) × Timepoint	-0.75	1.22	-0.61(1423)	0.542
(Feedback [Low] × Controllability [Low] × Maltreatment [Maltreated]) × Timepoint	2.21	1.73	-1.28(1423)	0.201
Random Effects				
σ^2	110.24			
$\tau_{00\ participant}$	502.99			
ICC	0.82			
N	477			
Observations	1908			
Marginal R^2 / Conditional R^2	0.078 / 0.834			

Note. Estimate represents unstandardised beta coefficient, SE represents standard error, t(DF) represent t value and degrees of freedom, p represents significance value, ICC represents intraclass correlation coefficient, σ^2 represents random effects residual, and $\tau_{00\ participant}$ represents participant random intercept.

†Degrees of freedom are rounded to the nearest whole number.

Supporting Table S8

Simple slopes of Timepoint by Group by Feedback interaction on goal-directed exploration

Group	Estimate	SE	*p*	p_{adj}
Group[Control], Feedback[Relative Positive]	0.64	0.19	< .001	.003
Group[Control], Feedback[Relative Negative]	-0.15	0.20	.445	.445
Group[Maltreated], Feedback[Relative Positive]	-0.20	0.20	.314	.445
Group[Maltreated], Feedback[Relative Negative]	0.17	0.19	. 375	.445

Note. Estimate represents unstandardised simple slope, SE represents standard error, p represents significance value, p_{adj} represents FDR-corrected p significance value.

Supporting Table S9

Linear mixed effects model results of change in exploration

Predictors	**Estimates**	**SE**	***t*(DF) †**	***p***
(Intercept)	8.04	0.65	12.35(923)	<0.001
Maltreatment [Maltreated]	-0.55	0.91	-0.60(932)	0.548
Feedback [Low]	0.11	0.92	0.123(923)	0.902
Controllability [Low]	-1.57	0.85	-1.84(923)	0.066
Timepoint	0.63	0.29	2.20(496)	0.028
Maltreatment [Maltreated] × Feedback [Low]	-1.55	1.28	-1.21(923)	0.227
Maltreatment [Maltreated] × Controllability [Low]	1.52	1.25	1.22(923)	0.222
Feedback [Low] × Controllability [Low]	1.25	1.23	1.02(923)	0.309
Maltreatment [Maltreated] × Timepoint	-0.70	0.40	-1.75(469)	0.081
Feedback [Low] × Timepoint	-0.74	0.41	-1.82(469)	0.068
Controllability [Low] × Timepoint	0.02	0.38	0.06(469)	0.950
(Maltreatment [Maltreated] × Feedback [Low]) × Controllability [Low]	-0.32	1.76	-0.18(923)	0.856
(Maltreatment [Maltreated] × Feedback [Low]) × Timepoint	1.12	0.57	1.99(469)	0.047
(Maltreatment [Maltreated] × Controllability [Low]) × Timepoint	-0.29	0.55	-0.52(469)	0.601

(Feedback [Low] × Controllability [Low]) × Timepoint	-0.10	0.54	-1.77(469)	0.861
(Maltreatment [Maltreated] × Feedback [Low] × Controllability [Low]) × Timepoint	0.08	0.78	0.10(469)	0.917
Random Effects				
σ^2	2.22			
$\tau_{00\ participant}$	11.77			
ICC	0.84			
N	477			
Observations	954			
Marginal R^2 / Conditional R^2	0.034 / 0.847			

Note. Estimate represents unstandardised beta coefficient, SE represents standard error, t(DF) represent t value and degrees of freedom, p represents significance value, ICC represents intraclass correlation coefficient, σ^2 represents random effects residual, and $\tau_{00\ participant}$ represents participant random intercept.

†Degrees of freedom are rounded to the nearest whole number.

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