Neuroscience and Biobehavioral Reviews 174 (2025) 106196

Contents lists available at ScienceDirect

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

Post-intervention neuroimaging effects of psychosocial interventions aimed at promoting resilience in children and adolescents under psychological stress: A systematic review

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ARTICLE INFO

Keywords:
Systematic review
Resilience
Youth
Neuroimaging
Interventions
Adversity

ABSTRACT

Childhood and adolescence are neurodevelopmentally critical periods, during which psychological adversity can increase the risk of subsequent mental health difficulties. However, the increased neuroplasticity during this window also confers potential for developing resilience, which is now seen as a dynamic process of adapting to adversity. This pre-registered systematic review (PROSPERO-CRD42024537715) summarises the post-intervention neuroimaging outcomes of non-invasive, non-pharmacological interventions aimed at promoting resilience in samples with a mean age of <25 years exposed to any explicit psychological stress. Studies involving traumatic or focal brain lesions were excluded. MEDLINE, PsycINFO and CENTRAL databases were searched from inception to 14/7/2024. Magnetic Resonance Imaging (MRI) outcomes were the primary focus. Risk of bias was assessed against adapted Joanna Briggs Institute checklist items. A narrative synthesis was conducted due to study heterogeneity. We identified 13 eligible studies: 1 reporting structural and diffusion-weighted MRI (performed after 2 years of intervention), 1 resting-state fMRI (14 years after end of intervention) and 11 task-based fMRI metrics (ranging from immediately post-intervention to 8 years after end of intervention). Resilience interventions reduce limbic activity (thalamus, amygdala and right anterior insula) in task-based fMRI. In older adolescents, social, mindfulness, and exercise interventions strengthen Prefrontal Cortex(PFC)-limbic connectivity, decreasing limbic activity. Evidence in younger adolescents is sparse, showing mixed effects on PFC-limbic connectivity. Five studies were at high risk of bias; the most common limitation was no pre-intervention MRI scans. Overall, this study summarises promising mechanisms, as demonstrated on neuroimaging, through which resilience can be enhanced in stressed youth through psychosocial interventions.

1. Introduction

Childhood and adolescence represent important periods of brain development. The neurodevelopmental definition of adolescence extends up to the age of 24 years, acknowledging that certain milestones continue to evolve during this time (Sawyer et al., 2018). This period is characterised by heightened brain plasticity, wherein the developmental trajectories of brain circuits are particularly sensitive to extrinsic influences and amenable to adaptation (Spear, 2013).

Adverse life experiences during this stage therefore have the potential to disrupt normal brain development and predispose individuals to negative mental health outcomes (Berens et al., 2017; Pollok et al., 2022). Adversity is defined as a chronic or severe psychological stress that is a deviation from an individual's expectable environment requiring adaptation (Mclaughlin, 2018).

Up to half of all children and adolescents in the developed world experience some form of adversity by the time they reach adulthood (Greif Green et al., 2010), which accounts for approximately half of the

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https://doi.org/10.1016/j.neubiorev.2025.106196
Received 7 February 2025; Received in revised form 26 April 2025; Accepted 1 May 2025
Available online 3 May 2025

incidence of mental health conditions in youth (Kessler et al., 2010). Exposure to childhood maltreatment, for example, is associated with increased likelihood of numerous subsequent mental health diagnosis, including approximately 2-fold increase in the odds of developing depressive, anxiety, alcohol-use or drug-use disorders and a 4-fold increase in post-traumatic stress (Teicher and samson, 2013).

The association between adversity and poor mental health outcomes is thought to be mediated by deleterious neurobiological effects of adversity on the developing brain (Tyrka et al., 2013; Mclaughlin et al., 2021). Whilst increased brain plasticity during childhood and adolescence confers increased risk of developing detrimental neurobiological changes under adverse conditions, it also confers increased potential to develop resilience.

The modern psychological concept of individual resilience is as a dynamic process – a set of positive adaptations that the individual can develop in response to the specific type of adversity they are under, which are associated with better-than-expected psychological outcomes given the nature and severity of their adversity exposure (Parsons et al., 2016; Luthar and zelazo, 2003; Rutter, 2013; Masten, 2011; Fergus and zimmerman, 2005).

Studies have demonstrated that resilience can be neurobiologically mediated by resistance to the initial stressful effects of adversity exposure, reversal of maladaptive changes after they develop, or, perhaps most interestingly, development of additional neurocircuitry that helps compensate for detrimental effects of adversity on the brain (Khalid et al., 2024; Teicher et al., 2016).

Neuroimaging is well-suited to investigate the dynamic neurobiological underpinnings of resilience. Magnetic Resonance Imaging (MRI) in particular has emerged as the primary imaging modality in such studies owing to its wide availability, lack of ionising radiation, high spatial-resolution, and ability to probe functional activation of brain regions through blood-oxygen level dependent (BOLD) imaging alongside structural brain changes depicting brain plasticity (Jensen et al., 2016; Davis et al., 2022).

Two recent systematic reviews have summarised a list of MRI brain features associated with resilience in young people from observational studies (Eaton et al., 2022; Zhang et al., 2023). These included greater ventromedial prefrontal cortex (vmPFC)-limbic functional connectivity during processing of negative stimuli and lower subgenual anterior cingulate cortex (sgACC) to Default Mode Network resting-state connectivity. The nature of these cross-sectional findings, however, remains unclear as observed associations with resilience do not support inference on causal links or dynamic changes.

Evidence from RCTs of pharmacotherapy and transcranial modulation have shown these clinical interventions are associated with dynamic changes in similar brain networks as identified by the abovementioned observational studies, which in turn track with and may drive beneficial mental health improvements (Gaffrey et al., 2011; Chen et al., 2023; Gallop et al., 2023).

For example, in adolescents with bipolar disorder, treatment with second generation antipsychotics followed by lamotrigine increased vmPFC fMRI activity from baseline when viewing emotional faces and normalised it toward that in healthy controls. These increases were associated with improvements in manic symptom scores (Passarotti et al., 2011). Repetitive transcranial magnetic stimulation (rTMS) targeted at the left dorsolateral PFC has been shown to increase resting-state functional connectivity between the left sgACC and left midcingulate cortex in adolescents, with associated improvements in depressive symptoms (Lu et al., 2023).

However, these interventions require clinical supervision and thus cannot be used by young people in the community who have not accessed healthcare services.

With the rising public awareness around mental health, there has been a surge in the popularity of supportive, behavioural, lifestyle and digital interventions purporting to help the general population manage stress and improve mental well-being (Pinto et al., 2021; Prince-embury and saklofske, 2014; Reavley et al., 2015). These have potential to be deployed in non-clinical youth-facing settings (e.g. schools, community centres, higher education institutions) or accessed by young people themselves with minimal or no clinical supervision (Das et al., 2016; Amiri et al., 2024; Grist et al., 2017). Efficacy of these interventions is being investigated while underlying mechanisms remain under-researched.

Few longitudinal studies provide first evidence that youth exposed to supportive psychosocial modifications develop brain changes that are correlated with improved psychological outcomes. For instance, improved family relationships during mid-adolescence were correlated with declines in risk-taking, which was mediated by reductions in ventral striatum activity (Qu et al., 2016).

Such studies have established dynamic behavioural correlations between brain changes and behavioural effects but are still limited by their naturalistic design. Evidence from well-designed experimental studies are required to establish if resilience promoting interventions induce specific brain changes, and if such changes mediate improvements in mental health. As such studies are beginning to emerge, a robust summary of causal neuroimaging changes resulting from these types of interventions would help identify:

(a) the most promising non-clinical interventions with respect to neuroimaging efficacy, and

(b) promising mechanistic brain targets through which resilience could be enhanced

In conjunction with future studies concerning acceptability, feasibility and real-world effectiveness, this knowledge could be used to inform neurobiologically effective, scalable public health interventions for youth exposed to significant psychological stressors.

The theoretical definition of adversity above is not so specific that a quantitative cut-off readily follows from it. However, the modern conceptualisation of resilience mandates that experiencing at least some psychological stress is a necessary condition for an individual to develop and substantiate resilience, and changes may be specific to the type of stress (Malhi et al., 2019; Rutter, 2013; Kalisch et al., 2015). Therefore, we were interested in neuroimaging changes associated with resilience in samples with exposure to an explicit psychological stress.

Childhood and adolescence are characterised by rapid periods of brain development, which may be a confound in observed associations between intervention and brain changes in observational studies (Eaton et al., 2022; Zhang et al., 2023). Neuroimaging resilience changes associated with interventions should therefore ideally be identified from controlled experimental designs.

Consequently, we conducted a systematic review of controlled experimental studies investigating the neuroimaging outcomes of non-pharmacological, non-invasive resilience interventions through MRI in children and adolescents exposed to an explicit psychological stress.

2. Methods

This systematic review was registered with the International Prospective Register of Systematic Reviews (PROSPERO Registration Number CRD42024537715).

2.1. Eligibility criteria

2.1.1. General

We included empirical research studies with a prospective controlled (with a parallel control group, or a within-subjects) design in human participants assessing MRI brain changes after resilience promoting intervention in young people exposed to adversity; published in peer-reviewed journals, where the full article was available in the English language. There was no restriction by type of study setting, geographical location or by publication date before the search date (14th July 2024).

2.1.2. Participants/population

We included studies where the mean (or median) age of the participants at the time of post-treatment MRI was < 25 years. Where the mean (and median) age was > =25 years, we examined if outcomes were reported separately for the subgroup of participants who were < 25 years of age and sought to include data for these participants.

We excluded studies that did not state the mean (or median) age; except in studies where we were confident that the participant group being referred to were aged < 25 years old (e.g. 'school children', or when the upper limit of the given age range was <25 years), in which case we included the study and contacted the corresponding author for this information.

We also excluded studies focusing on populations with acquired brain lesions such as traumatic brain injuries or focal brain lesions (e.g. secondary to vascular, neoplastic, infectious, inflammatory pathologies) which we expected would have pathology-related alterations in neurocircuitry.

2.1.3. Intervention(s), exposure(s)

We sought non-invasive, non-pharmacological behavioural, social, lifestyle, biofeedback or psychological interventions, therapies or programmes (hereafter referred to as 'psychosocial interventions') that were hypothesised to improve mental health, or brain features associated with mental health, in young people exposed to an explicit psychological stress.

The psychological stress was permitted to be of any type provided that it was named explicitly and shared by all participants within the study (except acute clinical or chronic pain as described below). This, for example, included pre-existing long or mid-term exposures (e.g. military deployment, poverty, deprivation), past exposures (e.g. victim of natural disaster, previous sexual abuse) or acute/experimentally-induced exposures (e.g. fearful stimuli, negative social feedback).

As the detrimental effects of stressful life experiences on the brain have already been relatively well-studied, we did not include studies that applied or removed a stressful condition alone (e.g. Sheridan et al. 2012; Bick et al. 2015; Ma et al. 2017). Also studies which examined the effect of an intervention on a population not reported to be exposed to an explicit psychological stress were excluded (e.g. Yuan et al. 2020; Patsenko et al. 2019; Slutsky-Ganesh et al. 2020).

We excluded studies where the key stressor or outcome was primarily based on acute pain in a clinical setting or chronic pain to avoid complexities. We excluded neuromodulation techniques that targeted one or more regions of the brain directly such as Electroconvulsive therapy, Transcranial magnetic/direct current stimulation, as well as more peripheral neuromodulation/stimulation techniques (e.g. vagal nerve stimulation) due to their distinct mechanistic effects, need for psychiatric workup and/or patient anaesthesia and are therefore unlikely to be suitable to be deployed to general youth population in non-specialist settings.

We excluded studies where the intervention was (wholly or partially) pharmacological or invasive. We included, however, studies concerning dietary modification (e.g. cod liver oil) that are available as dietary supplements, legal, taken orally, available over-the-counter i.e. without prescription in the United Kingdom.

2.1.4. Comparator(s)/control

We included studies with a controlled design - with either a parallel control group, or a within-subjects design featuring a period of no/control intervention.

2.1.5. Main outcome(s)

The childhood and adolescent periods are characterised by rapid brain development, which has potential to confound brain changes associated with development of resilience. Therefore, we primarily sought statistical comparisons of between-group differences in the longitudinal changes in MRI brain imaging features from pre-treatment to post-treatment. Where pre-treatment MRI was not performed, we extracted outcomes relating to between-group differences measured just at post-intervention imaging. We extracted effect size statistics of significant between-group differences (e.g. η2, partial η2, Cohen's D). Where this was not reported, we next sought reported effect size proxies of significant between-group differences (e.g. Z-score, T-score, F-statistic with degrees of freedom).

We aimed to investigate the protective brain effects of resilience interventions that are transferrable to the post-intervention period, rather than brain activity associated with the experience of the intervention itself. This was mainly relevant for fMRI, which potentially could have been performed whilst participants were actively engaging in the intervention (e.g. scan during meditation).

Therefore, we only included MRI outcomes that were acquired outside of periods of being actively engaging in a psychosocial intervention. For example, we would have included intergroup comparisons of fMRI changes after a period of a cognitive training intervention, but not during the training (examples of excluded outcomes can be found in these studies: Wu et al. 2021; López-Solà et al. 2019; Liu et al. 2020).

For task-based fMRI, outcomes were included provided the task was not identical to the intervention beforehand (e.g. fMRI scan during a reappraisal task after a re-appraisal training intervention would have been excluded for the same reason as above; examples of such excluded outcomes can be found in these studies: Greer et al. 2014; Cole et al. 2012; Hoefler et al. 2015).

Additional outcomes were statistical associations between MRI features found to be significantly different between the intervention vs. control group, and mental health (symptom or behavioural) outcomes.

2.1.6. Study search and data extraction

We searched Ovid MEDLINE (R) ALL (from inception [1974] to present), APA PsycINFO though the Ovid interface (from inception [1806] to present) and Cochrane CENTRAL (from inception to present), with the final search conducted on 14 July 2024. No search restrictions or filters were applied through Ovid's or Cochrane's interface.

The search strategies were peer-reviewed by a healthcare librarian with expertise in literature searches who was not otherwise associated with the project and are presented in Supplementary Material S1. The titles and abstracts identified from the search strategies were independently screened by two researchers (NJ and BJ) whilst blinded to the decisions of the other. We sought the full article for all studies that potentially met the eligibility criteria or could not be confidently excluded. For eligible studies, one researcher (NJ) extracted data, with one other researcher (BJ) checking for errors.

For our main outcome (between-group differences in MRI features) we extracted:

(a) Whether the MRI feature was a longitudinal change (i.e. difference between pre- and post-treatment MRI) or was measured at post-treatment MRI only.

(b) Whether the identified MRI feature was a result of exploratory whole-brain analyses or was part of specific set of regions of interest (ROI) in the study. We also extracted information on multiple-comparison correction methods used.

Negative results of between-group comparisons (i.e. null hypotheses that were accepted) are important findings, and we extracted them where reported for ROIs in the studies. For exploratory whole-brain analyses, however, (where between-group comparisons between many different brain regions are typically analysed simultaneously), we extracted regions significant under statistical comparison only, under multiple comparisons correction where performed.

Additional outcomes of our interest were results of mediation analysis between MRI features and mental health outcomes, but where such analyses were not conducted, we extracted results of correlation analyses.

2.1.7. Risk of bias and quality assessment

We are not aware of any risk of bias tool that is specifically designed for reviewing controlled developmental MRI studies. We therefore used relevant items from the Joanna Briggs Institute (JBI) checklists for RCTs (Barker et al., 2023) and Quasi-Experimental (Barker et al., 2024) studies in assessing methodology of studies with respect to our main outcome, but adapted certain items to imaging outcomes (described in Supplementary Table S2). We also assessed quality of studies by considering the overall risk of bias with additional metrics including MRI scan parameters.

Assessments were conducted independently by two researchers (NJ and BJ). Discrepancies in the final list of studies included, extracted data

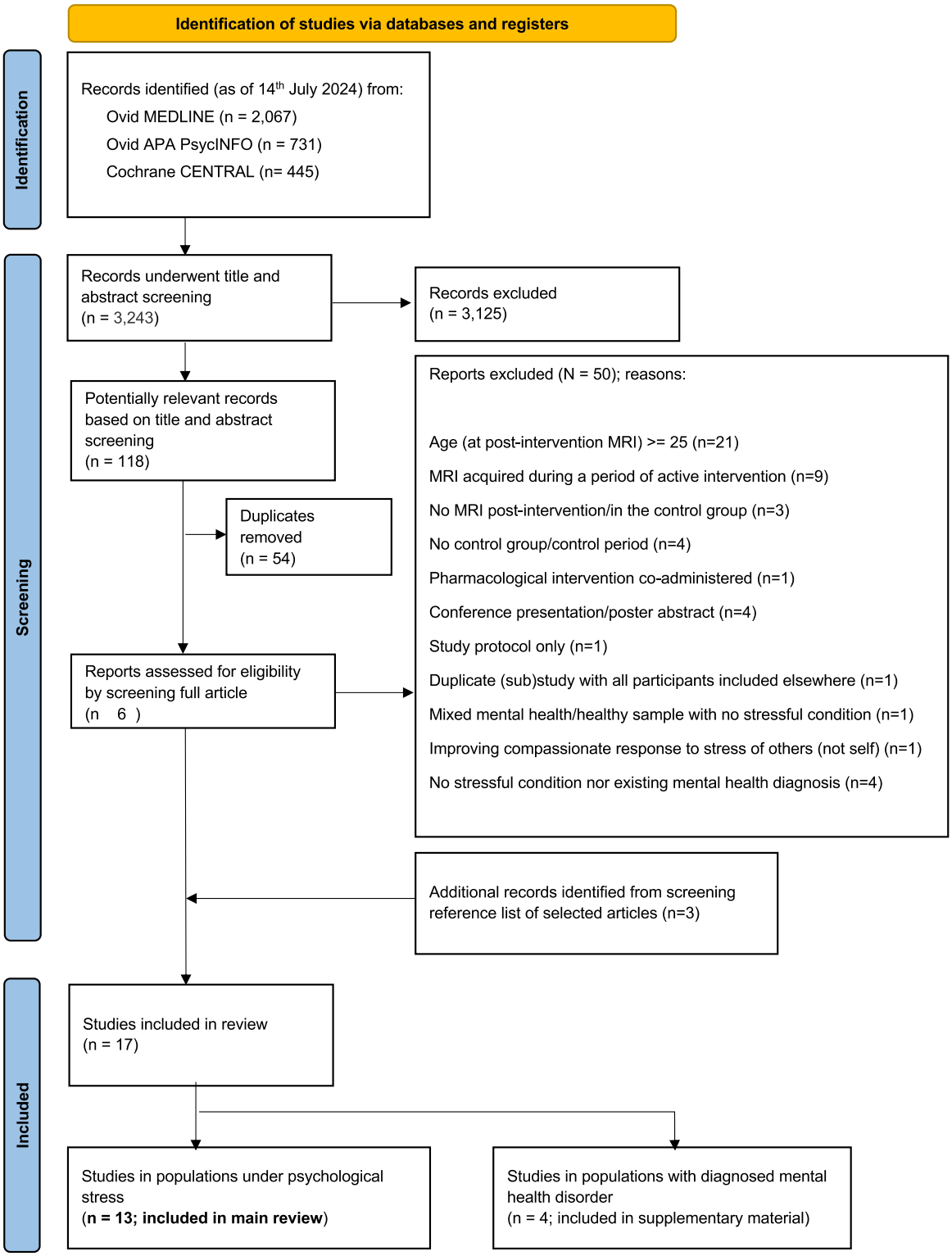

Fig. 1. PRISMA Flow Diagram of the study selection process.
Adapted from: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R. The PRISMA 2020 statement: an updated. guideline for reporting systematic reviews. bmj. 2021 Mar 29;372.

Table 1
Characteristics and summary of findings from studies reporting structural MRI outcomes of interventions to promote resilience under stress.

					Demographics			MRI			
Study	**Stressor**	**Intervention Condition**	**intervention duration/ intensity**	**Control Condition**	**Sample sizes**	**Age** Mean (SD) years	**Proportion (%) female**	**Interval between end of treatment to post-treatment MRI**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**
Habibi et al. (2018)	Participants from underprivileged (primarily Latino) minority communities of downtown Los Angeles	Music training	4–5 days (totalling 6–7 hours of music instruction) per week	Control Group 1: Sports training (Soccer programme) Control Group 2: Not engaged in any systematic after-school music or sports programme	Intervention Group = 18; Control Groups Combined = 38 (Control Group 1 = 18, Control Group 2 = 20)	[At baseline] Intervention Group = 6.70 (0.55); Control Group 1 = 6.93 (0.59), Control Group 2 = 7.13 (0.49)	Intervention Group = 5/18 (28 %); Control Groups Combined = 18/38 (47 %) [Control Group 1 = 10/18 (56 %), Control Group 2 = 8/20 (40 %)]	After ~2 years of treatment	Between-group differences in Pre to Post-treatment sMRI changes: No significant group differences in changes in thickness/ volume of selected regions of the frontal and temporal cortices, cingulate cortex, corpus callosum nor either cerebral hemisphere (p-values >.05)	Not performed	NA

Notes: SD = Standard Deviation; NA = Not applicable, sMRI = Structural MRI

and risk of bias were resolved by discussion, with DA arbitrating any non-resolved discrepancies.

3. Results

We identified 13 eligible studies which examined MRI outcomes of interventions to improve resilience in children and adolescents under psychological stress (Fig. 1). We also identified 4 further studies which examined MRI outcomes of interventions to improve psychological outcomes in youth with a diagnosed mental health condition. Living with an existing mental health disorder is recognised to be psychologically stressful (Gold, 2015; Yuii et al., 2007; Moon et al., 2014), but interventions in such studies sought to mitigate pathological neurocircuits that may be distinct from stressed (but healthy) youth, without manifest mental health condition(s). These are therefore not considered further in this main article but synthesised separately in Supplementary Material S3 and S4 for the interested reader.

Of the 13 studies, 5 were interventions targeting youth populations already being exposed to a particular psychological stress, while the other 8 studies induced a stressful condition on participants as part of an experiment. No studies were retrieved concerning interventions for stress experienced in the past. The median(range) of total participants in each study was N = 35 (93−11). The median (range) of participants in the intervention group(s) across the studies was n = 22 (44−14) and in the control group(s) was n = 18 (49−11). The age at post-intervention MRI ranged from 8.7 to 24.9 years old.

Three of these studies concerned the same longitudinal cohort, though reported imaging acquired at different timepoints (Habibi et al., 2018; Hennessy et al., 2019; Sachs et al., 2017). Two further studies concerned the same underlying cohort but reported the results from different tasks in task-based MRI (Haase et al., 2016; Johnson et al., 2014).

Two studies featured a within-subjects design, with imaging just after the intervention and control blocks. Of the 11 remaining studies which used a parallel control group, 5 studies featured imaging before as well as after the treatment period, allowing longitudinal comparison of changes between the intervention and control groups.

One study reported structural MRI (sMRI) outcomes (Tables 1), 1 reported resting-state fMRI (rs-fMRI) outcomes (Table 2), 11 reported task-based fMRI outcomes (Tables 3), and 1 (which also reported the sMRI outcome) reported Diffusion-Weighted Imaging (DWI)-based outcomes (Table 4).

Risk of bias was high in 5 studies and medium in 8 studies (Fig. 2) and varied across each outcome (Fig. 3). All 13 studies were deemed low quality with respect to our main outcome of interest (Supplementary Figure S5).

There was significant heterogeneity amongst studies, particularly with respect to intervention type, stressors and, for fMRI studies, the task performed during imaging. This precluded a meta-analysis; therefore a narrative synthesis has been used to summarise and explain findings.

3.1. Structural MRI

A single non-randomised low-quality study reported a sMRI outcome eligible for inclusion in this review (Habibi et al., 2018). This study featured structural imaging both before and after a 2-year follow-up period in a cohort of children (6–7 years old at baseline) recruited from an underprivileged Latin American minority community in the USA. The intervention was group music training, with control groups that did not participate in any musical training. There were no significant between-group differences in pre- to post-treatment changes in cortical thickness and volumes of the left or right cerebral hemispheres, corpus callosum, nor in regions of interest in the cingulate and temporal gyrus.

3.2. Resting-state fMRI

Hanson et al. (2019) conducted a study using participants from the Strong African Americans programme cohort (Brody et al., 2017), a randomised controlled study of a 7-week family-based sensitive parenting programme for African-American children aged 11 years of age at baseline, who were identified as being from poor households based on income-to-needs ratio. Greater connectivity between the right ventromedial pre-frontal cortex (vmPFC) and the dentate gyrus of the left hippocampus was demonstrated in the intervention compared to the control group when measured at 24 years of age. The strength of this connectivity negatively correlated with externalising symptoms across both intervention and control participants. Though there was a high risk of bias, as details of the control condition and demographics of participants included in the MRI analyses were unclear, this study is noteworthy due to the long interval of 14 years between the end of the intervention and MRI scan.

3.3. Task-based fMRI

Several studies reporting outcomes in this modality demonstrated that resilience interventions generally strengthened prefrontal-limbic connectivity to reduce limbic fMRI activity during stressful and emotional tasks. However, the direction of correlations varied across age groups.

Similar to Hanson et al. (2019); Valadez et al. (2024) investigated a parenting intervention for infants at high risk for homelessness/domestic abuse. Parents were randomly assigned to receive either a 10-session instruction programme on sensitive behaviours towards their infants or a control intervention that omitted this aspect of training. The MRI was also performed after a long period – approximately 8 years after the end of the treatment when the children were a mean age of approximately 10 years old. Children who had been in the sensitive parenting group demonstrated greater activation in the anterior cingulate cortex (ACC), and negative connectivity when viewing faces between the right PFC (including the ACC) and the amygdala. The control group demonstrated an opposite pattern of positive connectivity between these regions. Whole-brain analyses showed that PFC-amygdala connectivity mediated fMRI activity during this task in regions responsible for emotional processing, including the right insula, across both groups.

In older adolescents, intervention was associated with reduced PFC activity and positive correlations between key PFC and limbic regions. Mulej Bratec et al. (2020) conducted a within-subjects study in healthy females who were in late adolescence (mean age = 23 years) subjected to threatening stimuli (audio of fearful screams and shocks) during the experiment. The intervention was simply a video recording of a psychotherapist providing brief verbal support just before aversive stimuli runs, but this was effective at improving participants' emotional rating scores compared to the control condition (scrambled version of the supportive video messages). Mediation analyses showed that social support reduced fMRI activity during threatening stimuli in the ventromedial PFC and ACC, amongst other regions, which mediated reduced activity in the superficial amygdala and dorsomedial nuclei of the thalamus, and in turn improved emotional rating scores.

Morese et al. (2019) also investigated the protective neuroimaging effects of social support in a very similar cohort of healthy, all-female college students (mean age = 21 years), but the stressor was experimentally-induced social exclusion via the virtual cyberball game. Here, the support was provided before stressful runs by a friend of the same sex – either 'emotional support' via touching the participant's hand, or 'appraisal support' via providing text messages to help them reappraise the situation. Compared to the control group (where the friend remained in the same room but did not provide either support), the emotional hand-holding support group demonstrated reduced activity in the right anterior insula on whole-brain analysis. In contrast,

Table 2
Characteristics and summary of findings from studies reporting resting-state fMRI outcomes of interventions to promote resilience under stress.

					Demographics			MRI				
Study	**Stressor**	**Intervention Condition**	**intervention duration/ intensity**	**Control Condition**	**Sample sizes** Intervention Group; Control Group	**Age** Mean (SD) years	**Proportion (%) female** Intervention Group; Control Group	**Left handedness proportion (%)**	**Interval between end of treatment to post-treatment MRI**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**
Hanson et al. (2019)	**Poverty** – Participants from a rural Georgia county, with high community poverty indices as measured by income/needs ratio	Strong African American Families programme (a family skills training programme)	7 consecutive, 2-hour weekly meetings	Unclear	44; 49	11.2 (0.34) at baseline; 24.88 (0.61) at post-intervention MRI	24/44 (55 %); 24/49 (49 %)	0	~14 years	Between-group differences in Post-treatment rs-fMRI: Intervention group had greater connectivity between the left DG and the right vmPFC, (max voxel $t = 4.81$, $p = .05$, *corrected using cluster-size thresholding based on Monte Carlo simulation and mixed-model functions*)	Between-group differences in Post-intervention rs-fMRI: - Intervention group had Higher DG-right vmPFC connectivity ($t = +4.81$), and: -Lower DG-right inferior parietal lobule connectivity ($t = -4.00$) (both significant at $p = .001$, *Uncorrected*)	Higher DG-vmPFC connectivity negatively correlated with externalizing symptoms: $r = -5.97$ (95 % CI = −11.2, −1.10; $p < 0.05$). No significant associations between right DG- right inferior parietal lobe connectivity and externalizing behaviours

Notes: SD = Standard Deviation; rs-fMRI = resting-state fMRI; DG = dentate gyrus of the hippocampus; vmPFC = ventromedial pre-frontal cortex

Table 3
Characteristics and summary of findings from studies reporting task-based fMRI outcomes of interventions to promote resilience under stress.

					Demographics				MRI			
Study	**Stressor**	**Intervention Condition**	**intervention duration/ intensity**	**Control Condition**	**Sample sizes** Intervention Group; Control Group	**Age** Mean (SD) years	**Proportion (%) female**	**Left handedness proportion (%)**	**Interval between end of treatment to post-treatment MRI**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**
Zschucke et al. (2015)	**Adapted Montreal Imaging Stress Task** - mental arithmetic combined with social evaluative stressors	Aerobic Exercise	ran on a treadmill for 30 min at 60–70 % of their individual VO2max	Equivalent duration of placebo exercise (stretching)	18 (Highly-exercise trained = 10, sedentary = 8); 18 (Highly-exercise trained = 9, sedentary = 9)	Highly-exercise trained group = 24.40 (3.95); Sedentary Group = 24.63 (3.11)	0	0	Mean (SD) of 92.8 (± 10.7) minutes after treatment	Not performed	Between-group differences in Post-treatment fMRI during MIST task: - Intervention group had Greater activation in the bilateral hippocampus/ parahippocampal gyrus (peak Z-scores ranging from 4.57 to 4.13), and: -Lower activation in the right dlPFC and dmPFC, IFG, bilateral paracentral lobule, the pre- and postcentral gyri, the right MCC, and the right precuneus (peak Z-scores ranging from 4.55 to 3.85). No significantly different activation between the Highly exercise-trained and Sedentary participants. *(FDR threshold of $p < .05$, and cluster-level threshold corresponding to $p < .05$)*	Exploratory correlation analysis between MIST fMRI activation and changes in positive affect: Right dlPFC ($r = -.319$, $p < .001$, Bonferroni-corrected) Right IFG ($r = -.324$, $p < .001$, Bonferroni-corrected) No significant correlation between changes in positive affect and BOLD activity in the Right dmPFC, Right hippocampus or Left hippocampus.
Keynan et al. (2019)	**Military training** - Israeli Defence Forces combat soldiers during basic training and prior to operational deployment.	EEG-based Neurofeedback	6 neurofeedback sessions within a 4-week period, ~1–2 sessions/week.	No neurofeedback training (no placebo treatment)	30; 26	Not stated (range = 18–24 years **)	0	Not stated	~1 month after end of treatment	Between-group differences in Post-treatment fMRI during attention task: Intervention group had greater downregulation of amygdala signal in Regulate vs Sustained Attention contrast	Between-group differences in Post-treatment whole-brain analysis with amygdala cluster as a seed region: Intervention group had higher amygdala–vmPFC functional connectivity during both regulate and	No correlation between anxiety reduction and follow-up amygdala signal downregulation

(*continued on next page*)

Table 3 (*continued*)

					Demographics				MRI			
										(F(1,54) = 10.77, η2 = 0.17, 90 % CI: 0.04–0.31, p = 0.002, *single comparison only*)	attend conditions (p < .05, *FDR corrected)*	

					Demographics				MRI			
Study	**Stressor**	**Intervention Condition**	**intervention duration/ intensity**	**Control Condition**	**Sample sizes**	**Age** Mean (SD) years	**Proportion (%) female**	**Left handedness proportion (%)**	**Interval between end of treatment to post-treatment MRI**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**
Mulej Bratec et al. (2020)	**Aversive stimuli** - mild electric shocks and fearful screams	Videos with supportive communication from a psychotherapist	One short supportive sentence prior to each support run	Within-subjects design: Control condition was a scrambled version of the psychotherapist's support videos. Control runs took place on separate day for each participant, with run order counterbalanced across subjects.	27	23.6 (2.5)	All (100 %)	0	immediately after intervention/ control runs	Between-group differences in Pre vs. post treatment change in fMRI activation in ROIs during aversive stimuli was tested directly as mediator between social support and emotional rating scores (aversive feelings). Two-path mediation analysis: The (superficial) amygdala and (mediodorsal nuclei of) thalamus were negative mediators in relationship between social support and emotional rating scores – i.e. negative relationship between social support and fMRI activity, and positive relationship between fMRI activity and	Between-group differences in Pre vs. post treatment change in fMRI whole-brain activation during aversive stimuli: Two-Path Mediation Analysis: TPJ, dlPFC, inferior temporal cortex and cerebellum were positive mediators in the relationship between social support and aversive feeling scores - i.e. greater social support -> greater activity in these regions -> **increased** aversive feelings. Three-path Mediation Analysis: Bilateral postcentral gyri and the left angular gyrus were additional negative mediators; Right superior and bilateral mid temporal cortices	Please see preceding columns - fMRI activation during aversive stimuli was tested directly as mediator between social support and emotional rating scores.

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Table 3 (*continued*)

					Demographics				MRI			
										emotional rating scores. Three-path mediation analysis: OFC, vmPFC, dlPFC, ACC and MCC activity mediated the relationship between social support, activity in the amygdala and thalamus and aversive feelings – i.e. social support reduced activity in the OFC, vmPFC, dlPFC, ACC and MCC, which then reduced activity in the amygdala and thalamus during stimulus presentation, resulting in the reduction of reported negative emotions. (All results significant at $p < .05$, *FDR-corrected)*	were additional positive mediators between social support and thalamic-amygdala activity, aversive feelings. (All results significant at $p < .05$, *FDR-corrected)*

					Demographics				MRI			
Study	**Stressor**	**Intervention Condition**	**intervention duration/ intensity**	**Control Condition**	**Sample sizes** Intervention Group; Control Group	**Age** Mean (SD) years	**Proportion (%) female**	**Left handedness proportion (%)**	**Interval between end of treatment to post-treatment MRI**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**
Haase et al. (2016)	**Military training** – participants from marine infantry battalions undergoing pre-deployment training	Mindfulness-based mental fitness training	20-h course taught over 8 weeks	Usual pre-deployment training (no placebo treatment)	19; 16	Intervention Group = 22.35 (3.30); Control Group = 20.81 (1.10)	Not stated	Not stated	~ 2 weeks after end of treatment	Between-group differences in Pre to Post treatment change in fMRI during Behavioural interoceptive assessment task (consisting of anticipation, breathing restriction,	Not performed	Not analysed

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Table 3 (*continued*)

					Demographics				MRI			
									and post-restriction phases): During breathing restriction: Intervention group developed greater decrease in % signal change in the Right Anterior Insula. Across all three task phases combined: Intervention group developed greater decrease in ACC *(All results volume thresholded by clusterwise probability <.05)*			
Johnson et al. (2014)				19; 16	Intervention Group = 22.4 (3.1); Control Group = 20.9 (1.1)	Not stated	Not stated	~ 2 weeks after end of treatment	Between-group differences in Pre to Post treatment change in fMRI during Emotion Recognition: Intervention group developed greater decrease in %fMRI signal in the Right Anterior Insula (F (1150)= 6.34, p = 0.03), Right Posterior Insula (F (1150)= 21.33, p = 0.05), Ventral ACC (F(1150)= 14.48, p = 0.02), dorsal ACC (d = 0.86, F(1150)= 13.29, p = 0.04) *(p-values corrected for multiple comparisons; but method unclear)*	Not performed	Improvement in Resilience as measured by the Response to Stressful Experiences Scale correlated with reduction in right anterior insula activation (r = −0.42, p < 0.05)

					Demographics				MRI			
Study	**Stressor**	**Intervention Condition**	**intervention duration/ intensity**	**Control Condition**	**Sample sizes** Intervention Group; Control Group	**Age** Mean (SD) years	**Proportion (%) female**	**Left handedness proportion (%)**	**Interval between end of treatment to post-treatment MRI**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**
Morese et al. (2019)	**Social exclusion** via cyberball game	Two intervention groups: Emotional support and	Emotional Support Group: gentle touch from friend of same sex	Presence of friend, but without any support	Emotional Support Group = 23; Appraisal Support	21.67 (2.29) * *	All (100 %)	0	Immediately after treatment	Not performed	Between-group differences in Pre to Post-treatment change during Social Exclusion	In the emotional support group: No correlation between Δ activity in rAI and Δ

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Table 3 (*continued*)

					Demographics				MRI			
		Appraisal support.	Appraisal Support Group: text messages from friend to help reappraisal		Group = 23, Control Group = 25						(cyberball) task: After appraisal support, there was reduced activation in the right TPJ (Z = 3.42; t = 3.48; p = .046) and increased activation in left subgenual ACC (Z = 3.34; t = 3.39; p = .046) compared to control group. After Emotional support, there was reduced activity in the right anterior insula (Z = 3.29; t = 3.35; p = .052) compared to control group. *(p-values FWER-corrected)*	unpleasantness ratings In the appraisal support group: No correlation between Δ activity in rTPJ, and Δ unpleasantness ratings Positive correlation between Δ subgenual ACC and Δ unpleasantness ratings (r = 0.443, p < 0.017, *corrected for the number of correlations performed*).
Dutcher et al. (2020)	**Evaluative stress** - participants completed math problems with feedback designed to indicate they were performing progressively worse relative to an average peer	Self-affirmation: participants completed a task that had participants affirm their important values	As described in preceding column	Within-subjects design. In the control condition, participants completed alphabetizing trials controlling for visual content.	25	19.3 (1.35) * *	18/27 (67 %) * *	0	Immediately after intervention/ control runs	Not performed	Between-group differences in Pre to Post-treatment change during stress: No significant difference in Whole-brain fMRI activation during stressful trials (p < .05, *FDR-corrected).*	NA

					Demographics				MRI			
Study	**Stressor**	**Intervention Condition**	**Intervention duration/ intensity**	**Control Condition**	**Sample sizes** Intervention Group; Control Group	**Age** Mean (SD) years	**Proportion (%) female**	**Left handedness proportion (%)**	**Interval between end of treatment to post-treatment MRI**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**
Dettweiler et al. (2023)	**Montreal Imaging Stress Task** - participants had to solve arithmetic tasks under time	Education outside the classroom	1 school-day/ week in the forest, with 5 × 45 minute Science classes and 1 × 45 minute	Normal indoor lessons	30; 9 * **	Intervention Group = 10.3 (0.45); Control Group = 10.8	Intervention Group = 12/ 30 (40 %); Control Group = 4/9 (44 %) * **	Not measured * **	After 1 year of treatment	Between-group differences in Post-treatment fMRI during MIST: No significant group differences	Not performed	NA

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Table 3 (*continued*)

					Demographics				MRI			
	pressure and received negative social feedback		Physical Education over 1 school year			(0.68) * **				in activation of the hippocampus, amygdala or ACC for either stress>rest or stress>control contrasts within the 95 % Confidence Interval		
Valadez et al. (2024)	Participants were referrals from the Child Protection Service at high-risk due to homelessness or domestic violence	Early home-based Parenting Intervention to promote sensitive parenting (Attachment and Biobehavioral Catch-up programme)	10-sessions	Developmental Education for Families programme	21; 20	[At time of post-intervention MRI] Intervention Group = 10.1(0.8); Control Group = 9.9 (1.1)	Intervention Group = 9/21(43 %); Control Group = 11/20(55 %)	Not stated	~8 years	Between-group differences in Post-treatment fMRI connectivity between bilateral amygdalae and rest of the brain during Emotional Faces task: Fearful minus Neutral contrast: No significant group difference Neutral minus Fear contrast: No significant group difference Fearful + Neutral faces combined vs. blank screen: Intervention group had greater negative connectivity between the amygdala and right insula, right PFC and ACC *(thresholded at corrected cluster size Z > 2.3, p < .05, FWER-corrected via TFCE)*	Between-group differences in Post-treatment fMRI activity during Emotional Faces task for Fearful + neutral faces combined: Intervention group had greater activation in ACC, right OFC, and right insula; analysis showed this was mediated by amygdala-PFC connectivity. *(thresholded at corrected cluster size Z > 2.3, p < .05, FWER-corrected via TFCE)*	PFC activity for combined Neutral + Fearful faces was positively correlated with CBCL Total problems T-scores in the control group (p = .01), but not in the intervention group (p = .74)

					Demographics				MRI			
Study	**Stressor**	**Intervention Condition**	**intervention duration/ intensity**	**Control Condition**	**Sample sizes** Intervention Group; Control Group	**Age** Mean (SD) years	**Proportion (%) female**	**Left handedness proportion (%)**	**Interval between end of treatment to post-**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**

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Table 3 (*continued*)

					Demographics				MRI			
									treatment MRI			
Hennessy et al. (2019)	Participants from underprivileged (primarily Latino) minority communities of downtown Los Angeles	Music training	4–5 days (totalling 6–7 hrs of music instruction) per week	Control Group 1: Sport training (Soccer programme) Control Group 2: Not engaged in any systematic after-school music or sports programme	Intervention Group = 14; Control Group = 26 (Control Group 1 = 11, Control Group 2 = 15)	[At baseline] Intervention Group = 6.48 (0.42); Control Groups Combined = 7.04(0.49)	Intervention Group = 11/28 (39 %); Control Groups combined = 25/60 (42 %) [Control Group 1 = 12/29 (41 %), Control Group 2 = 13/31 (42 %)] * *	Not stated	Scanned after ~2 years, and ~4 years of treatment	Between-group differences in Pre to Post treatment change in fMRI activity during Colour-Word Stroop Task: No significant group differences after correcting for multiple comparisons in Year 4, nor Year 2 to Year 4 % signal change in the incongruent > congruent nor incongruent > rest contrasts	Between-group differences in Pre to Post treatment change: At Year 4 Post-Intervention scan, Intervention group had greater activation of the right inferior frontal gyrus (pars opercularis) in incongruent > rest contrast compared to the combined control group (Z = 5.08). No other significant group differences *(thresholded at corrected cluster size Z > 2.3, p < .05)*	Not analysed
Sachs et al. (2017)					Intervention Group = 14; Control Group = 30 (Control Group 1 = 13, Control Group 2 = 17)	[At post-intervention MRI] Intervention Group = 8.67 (0.42); Control Group 1 = 8.85 (0.62), Control Group 2 = 9.05 (0.44)	Intervention Group = 6/14 (43 %); Control Groups combined = 14/30 (47 %) [Control Group 1 = 8/13 (62 %), Control Group 2 = 6/17 (35 %)]	Intervention Group = 1/14 (7 %); Control Group 1 = 0/13 (0 %), Control Group 2 = 2/17 (12 %)	After ~2 years of treatment	Intervention vs. Control Group differences at Post-treatment fMRI Colour-Word Stroop task in the incongruent > congruent contrast: No quantified significant between-group difference reported	Between-group differences in Post-treatment fMRI in the incongruent > congruent contrast: Intervention group had greater activity in the bilateral lateral occipital cortices, cerebellum, IFG, pars opercularis, Precentral gyrus, Pre-SMA/SMA, Anterior cingulate regions, right lingunal gyrus, left anterior insula/frontal operculum and right insula compared to the control groups combined (Z-scores ranging from 4.75 – 2.70). Intervention group had greater activity in the	Not analysed

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Table 3 (*continued*)

	Demographics	MRI
		left lateral occipital cortex compared to Control Group 1 ($Z = 3.68$) (*thresholded at corrected cluster size $Z > 2.3$, $p < .05$*)

Notes: SD = Standard deviation; CI = confidence interval; MIST = Montreal Imaging Stress Task; PFC = prefrontal cortex; dlPFC = dorsolateral PFC; dmPFC = dorsomedial PFC; vmPFC = ventromedial PFC; IFG = inferior frontal gyrus; ACC = anterior cingulate cortex; MCC = middle cingulate cortex; OFC = orbitofrontal cortex; TPJ = temporo-parietal junction; SMA = supplementary motor area; FDR = False-Discovery rate; EEG = electroencephalogram; BOLD = Blood Oxygen Level Dependent; NA = Not applicable

* * = This demographic information is only given for an overall study sample, only a subsample of which had their MRI data included in the final analysis

*** = This demographic information was kindly provided by the study's corresponding author on request Dettweiler (2024)

the appraisal support group demonstrated increased activity in the subgenual ACC and right TPJ, with the former being positively correlated with increased aversive feelings.

In contrast to social support from others, Dutcher et al. (2020) investigated the resilience-conferring effect of self-affirmation in university students (mean age = 19 years) experimentally subjected to evaluative stress with feedback designed to indicate they were performing worse over time in a mathematics task relative to their peers. In this within-subjects study, whole-brain analysis demonstrated reduced activity in the left anterior insula during evaluative stress following self-affirmation runs compared to the placebo runs, though this was not significant after multiple comparison correction.

Two other studies also investigated effectiveness of interventions under evaluative stress using the Montreal Imaging Stress Task (MIST). Zschucke et al. (2015) investigated the effect of aerobic exercise in all-male participants where the intervention group exercised on a treadmill for 30 minutes at 60–70 % of their individual VO_{2max} compared to a control group performing an equivalent duration of exercise without significant cardiovascular activation. The fMRI MIST was conducted shortly after completion of the intervention (approximately 90 minutes), with lower activation in the right inferior frontal gyrus (IFG), right dorsolateral PFC (dlPFC), right dorsomedial PFC (dmPFC), right middle cingulate cortex (MCC), and right precuenus being demonstrated in the intervention group compared to control participants. Activity in these first two regions - the right IFG and dlPFC (but not dmPFC) - were negatively correlated with changes in positive affect. There was also greater activation in the right and left hippocampi/parahippocampal gyri in the intervention group, though this did not correlate with changes in positive affect. There was no difference in brain activation between participants who were highly-exercise trained versus those who reported being sedentary.

In contrast, Dettweiler et al. (2023) found no significant group differences in hippocampus, amygdala or ACC activation during MIST in German schoolchildren with a mean age of 10 years, after an intervention consisting of 1-year of 1-day-per-week education outside the classroom taught in a natural (forest) setting, compared to those who had normal indoor lessons. The intervention was designed to support autonomy, and greater perceived choicefulness was associated with higher hippocampal activation in the intervention group, suggesting that a more targeted intervention to develop this aspect may yield better results.

Keynan et al. (2019) investigated the effect of EEG-fMRI-based neurofeedback training via providing an animated representation based on amygdala EEG-fMRI activity in participants (aged between 18 and 24 years old) undergoing a stressful military training programme prior to operational deployment. This study borderline met our inclusion criteria as the task during fMRI acquisition was similar (though ultimately not identical) to the training intervention. Furthermore, there was no placebo/active control, with the comparison group undergoing normal military training. Unsurprisingly, the group who received the intervention were better able to downregulate their fMRI amygdala activity when instructed. The finding of interest, however, was that despite participants not being instructed on any particular cognitive strategy to downregulate their amygdala activity during training, whole-brain analysis showed greater vmPFC-amygdala connectivity in the intervention group.

Two other retrieved records also concerned a youth population (mean age of intervention group = 22 years) undergoing pre-deployment military training, which featured pre- and post-intervention MRI scans on the same underlying sample of participants (Haase et al., 2016; Johnson et al., 2014). The intervention was a mindfulness-based training course delivered over 8 weeks alongside usual military training, with the control group again only receiving the latter. The mindfulness group demonstrated greater signal reduction in the anterior insula and ACC across contrasts in emotional recognition and stressful breathing-restriction tasks measured as a percentage fMRI

Table 4
Characteristics and summary of findings from studies reporting Diffusion-Weighted Imaging outcomes of interventions to promote resilience under stress.

					Demographics			MRI			
Study	**Stressor**	**Intervention Condition**	**intervention duration/ intensity**	**Control Condition**	**Sample sizes**	**Age** Mean (SD) years	**Proportion (%) female**	**Interval between end of treatment to post-treatment MRI**	**Between-group differences in specified ROIs**	**Between-group differences in exploratory whole-brain analysis**	**Mental Health associations of significant MRI findings**
Habibi et al. (2018)	Participants from underprivileged (primarily Latino) minority communities of downtown Los Angeles	Music training	4–5 days (totalling 6–7 hrs of music instruction) per week	Control Group 1: Sport training (Soccer programme) Control Group 2: Not engaged in any systematic after-school music or sports programme	Intervention Group = 15; Control Group = 32 (Control Group 1 = 15, Control Group 2 = 17)	[At baseline] Intervention Group = 6.70 (0.55); Control Group 1 = 6.93 (0.59), Control Group 2 = 7.13 (0.49) * *	Intervention Group = 5/18 (28 %); Control Groups combined = 18/38 (47 %) [Control Group 1 = 10/18 (56 %), Control Group 2 = = 8/20 (40 %)] * *	After ~2 years of treatment	Between-group differences in DWI at 2 years post-treatment: No significant group difference in the FA or MD in Multiple cortical regions, including motor, sensory, and association areas, as well as the precuneus and corpus callosum ($p > .05$, *Bonferroni correction*).	Not performed	Not analysed

Notes: SD = Standard deviation; NA = Not applicable; FA = Fractional Anisotropy; MD = Mean Diffusivity * * = This demographic information is only given for an overall study sample, only a subsample of which had their MRI data included in the final analysis

signal change from their pre-intervention scan. Reduction in right insula activation was negatively correlated with improvement in Response to Stressful Experiences Scale scores.

Two non-randomised studies (Hennessy et al., 2019; Sachs et al., 2017) shared the same underlying cohort of children (6–7 years old at baseline) with each other as well as the study reporting sMRI and DWI outcomes (Habibi et al., 2018). Recruitment was from underprivileged Latin American minority communities in the USA. These investigated the effect of group music training. In each study, two comparison groups that did not participate in any musical training were used – one with participants that played sports, and the other where they participated in neither sports nor music. In pre-defined regions of interest, which included the pre-SMA/SMA, left IFG, and left ACC, there was greater percentage signal change between incongruent and congruent conditions in the intervention group after 2 years of training, suggesting music training promoted increased recruitment of these executive function areas for inhibitory control. This group difference, however, was not significant under multiple comparison correction after 4 years of intervention. Exploratory whole-brain analyses revealed a handful of other regions with significantly different activation between groups at both 2 and 4 years of intervention, but associations with psychological outcomes were not examined, thereby making it unclear if these changes conferred any resilience to the detrimental neuroimaging effects of poverty (Lipina and evers, 2017).

3.4. DWI

Only a single study, (Habibi et al., 2018), reported DWI outcomes. This non-randomised study assessed as being at high risk of bias used the same cohort of underprivileged minority youth as the two studies described above. There were no significant group differences in the Fractional Anisotropy (FA) after Bonferroni correction for multiple comparisons, nor Mean Diffusivity (MD) of the corpus callosum (CC) at the uncorrected level, when measured after two years of music training. There was greater FA in the intervention group compared to the two control groups combined in the CC adjacent to the superior frontal gyrus and precentral gyrus which were significant at the uncorrected alpha $< .05$, though associations with psychological outcomes were again not examined.

4. Discussion

In this review, we have summarised the post-intervention neuroimaging outcomes associated with psychosocial interventions aiming to improve resilience in youth under stress.

Resilience interventions were associated with reduced limbic (right anterior insula, thalamus, amygdala) activity during task-based fMRI. Some studies demonstrated that interventions were associated with task-based fMRI changes in key prefrontal regions (vmPFC, dlPFC, and ACC) and PFC-limbic connectivity, though effects varied by age. In studies with older adolescent samples (mean age $\geq$ 22 years), PFC activity and positive PFC-limbic connectivity increased, while in a sample of younger adolescents (mean age 10 years), activity in the PFC was lower in the intervention group, alongside more negative PFC-amygdala connectivity. These changes collectively contributed to reduced limbic activity.

In the systematic review of observational studies by Eaton et al. (2022), greater PFC-mediated control over the amygdala was also identified as one of the key markers of resilience. Taken together, this suggests that resilience can be enhanced by strengthening PFC-limbic circuitry to control limbic activity during negative stimuli, which cognitively seems to correspond with greater emotional control during stress (Lee et al., 2012).

Our review featured an EEG-fMRI neurofeedback intervention aimed at helping a sample of all-male participants exposed to a threatening environment specifically downregulate their amygdala activity on demand (Keynan et al., 2019). The interesting finding was the

Study	Active placebo used in control group/during control period	Random allocation	Concealment prior to group allocation	Participant blinding	Equal group characteristics at baseline	Characteristics of final sample included in MRI analyses	MRI Pre- and Post- treatment	Regions of Interest (or use of whole-brain analysis) specified in pre-published/registered protocol	MRI software Package Used	Multiple comparison correction	Overall Risk of Bias
Habibi et al. (2018)					*	*	*		(a)	*	
Hanson et al. (2019)					**				(b)		
Zschucke et al. (2015)									(c)		
Keynan et al. (2019)									(d)		
Mulej Bratec et al. (2020)		*					**		(e)		
Haase et al. (2016)									(b)		
Johnson et al. (2014)					***				(b)		
Morese et al. (2019)									(e)		
Dutcher et al. (2020)		*					**		(c)		
Dettweiler et al. (2023)									(e)	NA	
Valadez et al. (2024)									(f)	**	
Hennessy et al. (2019)					*				(f)		
Sachs et al. (2017)									(f)		

Key for colour codes	Active placebo treatment in control group/control period	Random allocation	Allocation concealment	Participants blinded to treatment received	No significant differences in baseline characteristics	Demographics reported for subsample included in MRI analyses, and separately for intervention and control group participants	MRI scans Pre- and Post- treatment	All region(s) of interest/whole-brain analyses in the study were pre-specified in referenced protocol/registration	Commercially available/open-source imaging analysis pipeline used	Appropriate use of named multiple comparisons correction method	Low
		Pseudorandomisation (for studies with parallel control group)	Unclear or Not applicable		Unclear	Demographics reported for subsample included in MRI analyses, but not separately for intervention and control group participants.	Some, but not all, MRI metrics analysed longitudinally	Some, but not all, region(s) of interest/whole-brain analyses in the study were pre-specified in referenced protocol/registration	Imaging pipeline not available publically	Use of multiple comparison corrections stated, but method unclear	Medium
	No active treatment in control group/control period	Non-randomised study	No allocation concealment	No effective blinding	Differences in characteristics at baseline	Demographics not reported, or reported only for the overall study sample prior to dropout/data exclusion from MRI analysis	Metrics from Post-treatment MRI only	No protocol/registration referenced; or MRI analyses plan not specified therein	Imaging pipeline not specified	No/unclear if used	High
Notes		For within-subject designs, randomisation or pseudorandomisation (to ensure equal number of participants underwent each possible order) would be evaluated as low risk of bias in this category. *counterbalanced			Differences in baseline: *Age (Intervention < Control) ** Family socio-economic status risk (Intervention > Control) *** Sleep Quality (Intervention > Control), and proportion Married (Control > Intervention)	* for sMRI only, not for DWI	*for sMRI only, not for DWI ** within-subjects design		a) BrainSuite (b) Analysis of Functional NeuroImages (AFNI) (c) Statistical Parametric Mapping software Version 8 (SPM8) (d) BrainVoyager QX version 2.8 (Brain Innovation) (e) Statistical Parametric Mapping software Version 12 (SPM12) (f) FMRIB Software Library (FSL)	This was assessed for the main ROIs. If the main ROI was not significant, or if whole-brain analysis only, then this was assessed for the latter. If no significant findings at the uncorrected level, then marked as Not Applicable (NA) *likely Bonferroni correction for DWI. NA for sMRI **randomise-corrected	

Fig. 2. Risk of Bias assessment for included studies.

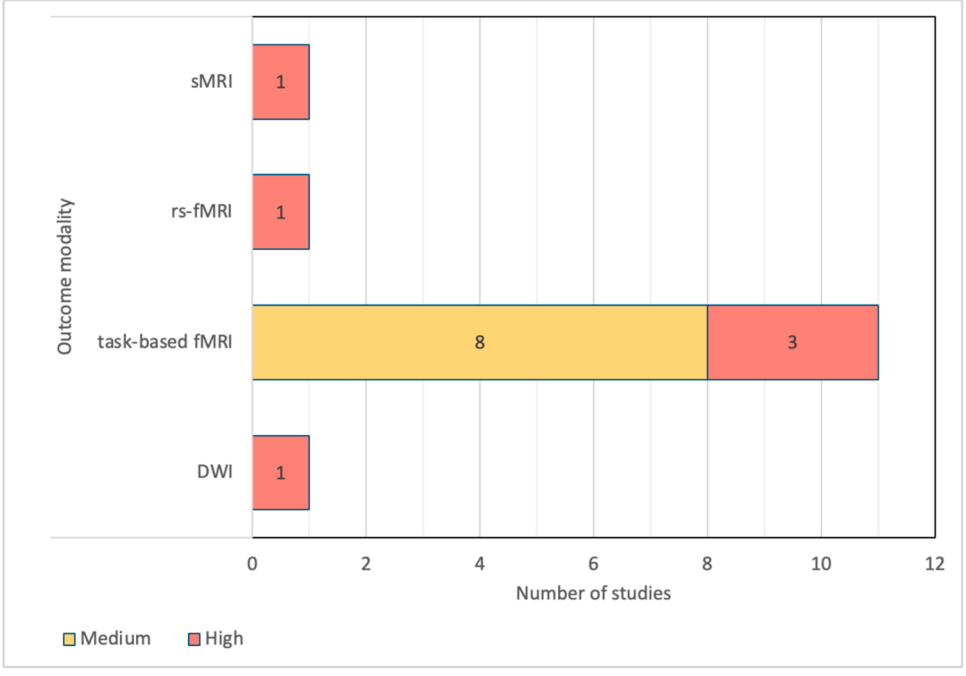

Fig. 3. Risk of bias across different MRI modalities.

development of greater vmPFC-amygdala connectivity in the intervention group despite participants not being instructed on (and therefore presumably free to choose) any particular cognitive strategy during training. Taken together with results of the other task-based fMRI studies, this suggests that (ventromedial)PFC-amygdala neurocircuitry may be a particularly amenable and relatively intervention-agnostic pathway for developing resilience. Supporting this, decreased vmPFC was shown to mediate decreased amygdala activity and improve emotional rating scores in Mulej Bratec et al. (2020) despite featuring a different intervention (social support), sex (all-female sample) and stress (acute experimentally-induced startling stimuli).

An analogous finding was replicated during resting-state connectivity (Hanson et al., 2019) where parenting intervention was associated with increased vmPFC-hippocampal connectivity by late adolescence, the strength of which was associated with lower externalising symptoms. This connectivity pattern has also been found in an observational study of resilience in previously institutionalised youth, where greater vmPFC-hippocampal connectivity during an aversive-learning task was associated with lower anxiety symptoms 2 years later (Silvers et al., 2016).

Resilience interventions were also generally associated with decreases in dlPFC activity which, primarily by reducing activity in the amygdala, improved mental health symptoms under stress. This finding was seen in two studies (Zschucke et al., 2015; Mulej Bratec et al., 2020) that varied in intervention (acute exercise vs. social support), stressor (social evaluative stress vs. aversive sensory stimuli) and sex (all male vs. all female participants), though both were conducted in older adolescents (mean age 23–24 years). However, it is increased dlPFC activity that is typically considered to downregulate emotion (Nishiyama et al., 2015; Koban et al., 2017; Achterberg et al., 2020), and it is presently unclear why this pattern was observed in the intervention studies in our review which future studies should investigate.

Eaton et al. (2022) reported in their review (which only included studies with mean age up to 19 years) that, in contrast to other parts of the PFC, they did not find the ACC as being involved in the top-down regulation of amygdala during stress. We also found no direct evidence for this, but did find that resilience interventions in general decreased ACC activity during task-based fMRI in older adolescents (mean age $\geq$ 22 years), which mediated improved emotion via reducing thalamic activity (Mulej Bratec et al., 2020), or was associated with reduced anterior insular activity (Haase et al., 2016; Johnson et al., 2014). The latter was also demonstrated in an observational study (Eckstrand et al., 2019) in a similar age group.

An interesting finding was that social support interventions (Mulej Bratec et al., 2020; Morese et al., 2019) were associated with altered fMRI activity in the TPJ (increase in former study, decrease in the latter) and increased fMRI activity in the (subgenual) ACC during acutely induced stress, which in turn was associated with an increase in unpleasant emotions in participants, opposing the calming effects of other circuits described above. The TPJ is a key structure implicated in the Theory of Mind (Stevens et al., 2011; Abu-akel and shamay-tsoory, 2011), and such brain activity may be protective by helping motivate individuals to withdraw from negative stimuli or social relationships (Sturgeon and zautra, 2016).

From the perspective of intervention types, the RCT evidence suggests that social support, mindfulness-based and acute physical exercise interventions are associated with decreases in activity in key PFC regions (namely the vmPFC, dlPFC and ACC), and enhancing positive PFC-limbic connectivity, thereby reducing limbic activity during stress in older adolescents (mean age $>$ 21 years old). For younger youth ($<$12 years old at start of intervention), the evidence is sparser and more inconsistent. The two RCTs reporting positive findings (Hanson et al., 2019; Valadez et al., 2024) concerned social interventions delivered at the family-level, which were associated with higher vmPFC-DG connectivity in rs-fMRI, and more negative PFC-amygdala connectivity during task-based fMRI.

DWI outcomes were only reported in a single, non-randomised study (Habibi et al., 2018) concerning a music intervention for underprivileged youth which identified greater FA in the corpus callosum (CC) adjacent to the superior frontal gyrus, and precentral gyrus, though these were not significant after applying the stringent Bonferroni correction.

As identified in Eaton et al. (2022), resilience has been associated with increased FA values in the CC across existing observational studies in youth. In particular, a sample of youth from the IMAGEN dataset (Galinowski et al., 2015) who were at low risk of mental health disorder despite having experienced high cumulative life stressors (including illness, accidents and bereavements) had increased FA values in the anterior CC, with tractography centred on this seed region demonstrating these fibres subserved the ACC and frontal cortex. The ACC is an important limbic structure in modulating emotional pain (Braem et al., 2017), and improvement in FA would complement functional connectivity changes in this region as described above. In future, higher-quality randomised studies studying diffusion metrics of this region in response to intervention would be helpful.

5. Limitations

Studies investigating neuroimaging outcomes of resilience-conferring interventions for youth under stress were relatively few, and heterogenous with respect to intervention and stressor.

We retrieved only one study reporting sMRI and DWI outcomes, which was non-randomised and essentially reported null findings only (Habibi et al., 2018). Even allowing for the rapid developmental changes that occur during youth, structural and microstructural brain changes require comparatively longer follow-up periods (months to years) to be appreciable on neuroimaging, which makes follow-up and attrition particularly challenging (although this has been achieved in a prior study (Brody et al., 2017)).

Turning to fMRI studies, although most measured neuroimaging changes after weeks to years, some (Mulej Bratec et al., 2020; Morese et al., 2019) performed post-intervention MRI immediately after the end of an acute intervention. It is unclear whether these post-treatment neuroimaging changes would have conferred lasting benefit over a longer period. Where possible, future studies could consider assessing progression of neuroimaging changes at multiple timepoints after the end of intervention.

The other major limitation across studies was that stressors were defined in terms of the environment or exposure (e.g. poverty, military training) rather than quantitative scores reflecting individual levels of perceived stress. It is unclear to the extent that a given participant was truly experiencing stress levels sufficient to be considered adversity as per its theoretical definition above as a deviation from the individual's typical environment requiring resilient adaptation (Mclaughlin, 2018). This could have been a source of confounding in the identified between-group differences. Future studies should measure these and consider including them as co-variates in the analysis of post-intervention neuroimaging changes.

Although many studies investigated the effect of an intervention on a brain circuit already known to be affected by or associated with resilience to a particular stressor, only 5 of the 13 studies explicitly analysed relationships between MRI and mental health outcomes. This was a particular problem in studies using exploratory whole-brain techniques, where a lack of such analyses meant it was unclear if brain differences between intervention and control groups would have been meaningfully associated with improved psychological outcomes.

6. Conclusion

In summary, social support, mindfulness-based and acute physical exercise interventions in older adolescents (with a mean age $>$ 21 years) are associated with decreases in activity in key PFC regions (namely the

vmPFC, dlPFC and ACC), and enhancing positive PFC-limbic connectivity, thereby reducing activity in limbic structures such as the anterior insula, thalamus and amygdala during stress.

Evidence on resilience interventions in younger adolescents is sparse and inconsistent, compounded by limited studies concerning structural or DWI-based brain changes. Quantitative measurements of stress and adversity, as well as their integration as covariates in analyses of MRI changes and psychological outcomes, remain key gaps. Future studies should prioritise longitudinal analyses and inclusion of comprehensive mental health assessments.

Overall, our review highlights the post-intervention neuroimaging changes of existing psychosocial resilience interventions in children and adolescents, which can inform development of supportive interventions in the general youth population exposed to psychological stress.

Funding sources

Salary support was provided for NJ from the Midlands Mental Health and Neurosciences programme for Healthcare Professionals, Wellcome Trust.

Declaration of Competing Interest

The authors declare no competing interests

Acknowledgements

The authors thank Kate Freeman, Research Librarian at the University of Nottingham, for their kind assistance in building and reviewing the search strategy.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2025.106196.

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