

REVIEW

Modulation of early stress-induced neurobiological changes: a review of behavioural and pharmacological interventions in animal models

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Childhood adversity alters the predisposition to psychiatric disorders later in life. Those with psychiatric conditions and a history of early adversity exhibit a higher incidence of treatment resistance compared with individuals with no such history. Modulation of the influence early stress exerts over neurobiology may help to prevent the development of psychiatric disorders in some cases, while attenuating the extent of treatment resistance in those with established psychiatric disorders. This review aims to critically evaluate the ability of behavioural, environmental and pharmacologic interventions to modulate neurobiological changes induced by early stress in animal models. Databases were systematically searched to locate literature relevant to this review. Early adversity was defined as stress that resulted from manipulation of the mother–infant relationship. Analysis was restricted to animal models to enable characterisation of how a given intervention altered specific neurobiological changes induced by early stress. A wide variety of changes in neurobiology due to early stress are amenable to intervention. Behavioural interventions in childhood, exercise in adolescence and administration of epigenetic-modifying drugs throughout life appear to best modulate cellular and behavioural alterations induced by childhood adversity. Other pharmacotherapies, such as endocannabinoid system modulators, anti-inflammatories and antidepressants can also influence these neurobiological and behavioural changes that result from early stress, although findings are less consistent at present and require further investigation. Further work is required to examine the influence that behavioural interventions, exercise and epigenetic-modifying drugs exert over alterations that occur following childhood stress in human studies, before possible translational into clinical practice is possible.

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INTRODUCTION

Childhood adversity affects up to 40% of children raised in the West.¹ Psychiatric conditions such as anxiety and depressive disorders, schizophrenia and autism spectrum disorders have each been associated with stress in childhood.^{2–6} The neurobiological and psychosocial implications of early adversity have also been associated with the development of other disorders in which stress plays a role, such as cardiovascular disease, type 2 diabetes mellitus and obesity.^{7–9}

Psychiatric disorders are projected to become the second leading cause of morbidity in 2020.¹⁰ As individuals exposed to stress in childhood display an enhanced susceptibility to these conditions, modulation of the neurobiological sequelae that result from early adversity may represent a novel target for the reduction or even prevention of chronic stress-related disorders, potentially alleviating their significant burden on the health-care system.

Animal models enable characterisation of the spectra of neurobiological alterations induced by early stress, determination of which is not possible through human studies. A number of animal models of early adversity exist. Although differing in specifics, each centres on the importance of the mother for normal development, and as such involve manipulation of this relationship.¹¹ Animal models enable delineation of the

mechanism by which a given intervention exerts its effect on a specific neurobiological change that is often not possible in clinical intervention studies.

To date, there has been no comprehensive review detailing the mechanisms and effects of interventions on the deleterious alterations in neurobiology induced by childhood stress. The objective of this review is therefore to present the current evidence in order to critically evaluate whether behavioural interventions, environmental enrichment (EE) and pharmacological interventions have properties that modulate the neurobiological alterations that result from early adversity. This review focuses on describing interventions and the mechanisms underlying their ability to modulate early stress-induced neurobiological changes using animal models. From a translational perspective, the results of this review may stimulate research in humans that were exposed to early life stress and adversity.

METHODS

The PubMed, Medline and PsychInfo databases were searched to identify literature to conduct this review. In brief, the search was performed to identify works demonstrating modulation of changes in neurobiology induced by early stress in animal models. The search terms ('stress, psychological' [MeSH] or 'maternal deprivation' [MeSH] or 'maternal separation') and ('therapeutics'

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[MeSH] or 'drug therapy' [MeSH] or 'modulation' or 'intervention') and ('models, animal' [MeSH]) were used, and limits were set to articles published between 1980 and 2013 and in the English language. Reference lists were cross-referenced to locate additional works. In total, 242 full-text articles were identified after assessment of abstracts pertaining to these criteria. To determine inclusion of full-text articles within this review, animal models of early stress were restricted to those involving manipulation of the mother–pup relationship, including maternal separation, maternal deprivation, variations in maternal care and exposure to an abusive mother during childhood. Animal models examining the ability of intervention to modulate changes induced by neonatal immune challenge with lipopolysaccharide (LPS) were excluded, as were interventions that occurred exclusively before early stress exposure. Finally, 86 full-text articles were excluded on the basis of these criteria and 158 articles were included in the final analysis.

ANIMAL MODELS OF EARLY LIFE STRESS

A number of animal models of early life stress exist. Those commonly utilised include those that involve manipulation of the mother–pup relationship such as maternal separation and maternal deprivation. Paradigms differ in specifics, however generally maternal separation refers to separation of pups (either individually or as a group) from the dam for 2–6 h daily from post-natal day (PND) 14 or 21, although paradigms exist that involve separation for differing lengths of time. Maternal deprivation represents a more severe form of early life stress, and involves separating pups from the dam for a single 24-h period during early post-natal life, usually on PNDs 3 or 9. Exposure to an abusive mother during the post-natal period represents another animal model of early life stress.¹² While not early life stress *per se*, models that examine the impact of variations in maternal care enable characterisation of the influence low versus high levels of care exert on offspring.¹³ Bedding deprivation is another form of early stress, in which reduced volumes of bedding are provided to the stressed group. Stress occurs as a result of abnormal fragmented interactions with the dam due to limited bedding material.¹⁴ Disrupted long-term potentiation and decreased numbers of dendritic spines in the hippocampus,¹⁵ considered correlates for learning and memory¹⁶ and synaptic plasticity respectively,¹⁷ have been reported in models utilising bedding deprivation. Neuroendocrine alterations have also been demonstrated following bedding deprivation, with reports of elevated basal plasma corticosterone levels and reduced corticotropin-releasing hormone (CRH) mRNA expression in the hypothalamus in adulthood.¹⁴ Research is yet to assess the effect that interventions exert on changes induced by bedding deprivation; hence, such studies will not be addressed in this review.

The influence of interventions on changes in neurobiology caused by early life stress is complicated by the use of a variety of different control groups. In brief, control groups include those that are either stressed without an intervention or non-stressed with and without an intervention. Consideration of the control groups helps determine the influence a given intervention exerts under different treatment conditions.

FACTORS INFLUENCING THE EFFECT OF EARLY LIFE STRESS

The long term influence early stress exerts on neurobiology and the longevity of these changes are dependent on a number of factors. (1) The nature of early stress: as discussed previously, there are a number of animal models that involve manipulation of the mother–pup relationship (that will be discussed in depth in this review). (2) The developmental period in which stress occurs: the brain displays enhanced plasticity during times of rapid brain development, making it more vulnerable to perturbations in the environment during this time. Stress exposure during the early

post-natal period, later childhood and early adolescence exerts a disproportionately large effect on the developing brain.¹⁸ (3) The duration of stress exposure and (4) the age of assessment. (5) Finally, maternal separation studies indicate that rats and mice respond differently to stress early in life; species and strains must be taken into consideration when interpreting study findings. Enhanced basal neuroendocrine reactivity has been reported in rats following maternal separation^{19,20} while unaltered neuroendocrine activity has been widely reported in mouse models.^{21,22} Similarly, rats display enhanced anxiety^{23,24} and depression-like^{19,25} behaviours after early stress. Mixed reports exist in mice, once again with unchanged behaviour in mouse models,^{22,26–29} although findings are varied. As each of these factors ultimately influences the long-term sequelae of early adversity, it is likely that they also influence the way in which interventions alter changes in neurobiology.

EARLY LIFE STRESS INDUCES CHANGES IN NEUROBIOLOGY

Although predominantly controlled by genetic factors, the nature of the early environment influences development.³⁰ The immature nervous, endocrine and immune systems share an intertwined ontogenesis,³¹ with stimulation of one during early life may ultimately impact the development of the others.³² Depending on the quality of the environment early in life, maturation is programmed along a specific axis. Stress exposure in childhood may therefore set the stage for a stress-susceptible phenotype, enhancing the predisposition to psychiatric disorder development in adulthood.

Findings from animal models of childhood adversity indicate that early stress influences behaviour, with reports of enhanced anxiety^{23,24,33} and depression-like^{19,25,34–37} behaviour and impaired spatial learning and memory^{23,38–40} after early stress. At present, the specific neurobiological changes underlying these behavioural changes remain to be fully characterised. Animal studies indicate that early stress exerts wide-ranging effects within the brain at a cellular level, with altered neuroendocrine activity, immune function and neurotransmission reported after early adversity. Changes often occur within specific brain regions. Studies to date have predominantly focused on the influence it exerts over the hippocampus and prefrontal cortex, although some works examine changes in the amygdala secondary to early adversity. Similarly interventional studies tend to investigate the ability of interventions to modulate changes in the hippocampus and prefrontal cortex caused by early stress; such modulatory influences will be examined in detail throughout this review.

Although inconsistencies exist across the literature, evidence suggests that early stress enhances basal hypothalamo–pituitary–adrenal (HPA) axis activity,^{19,23} both augmented^{41,42} and attenuated⁴³ neuroendocrine responses to later stress have been shown in animal models. Impaired cell-mediated immune function has been demonstrated in both non-human primate^{44–46} and rodent^{47–50} models of early stress, alongside elevated basal pro-inflammatory activity.⁵¹ Reports from animal studies remain divided as to whether subsequent inflammatory responses are enhanced^{52–54} or reduced^{51,54,55} following early stress.

Neurotransmitter systems appear vulnerable to adversity early in life. Reduced serotonin receptor expression has been demonstrated in the prefrontal cortex,^{56,57} hippocampus^{56,57} and raphe nucleus^{22,58} following early stress in animal models, indicating that adversity impairs serotonergic signalling. Reports also indicate that early stress influences dopaminergic signalling; decreased activity of the mesolimbic dopaminergic system has been demonstrated following separation, once again in line with depression-like behaviour.⁵⁸ Alterations in social,⁵⁹ anxiety⁵⁷ and depression-like^{58,60} behaviours have each been associated with altered monoaminergic neurotransmission in several works. Similarly decreased expression of parvalbumin, a GABAergic

Table 1. Behavioural interventions modulate early stress-induced changes

| Reference | Objective | Early stress | Intervention | Assessment age | Outcome measures | Results | Interpretation |
|-----------|---|--|---|-----------------|---|---|--|
| 63 | <i>Modulation of early stress-induced changes by cross-fostering</i> Determine the ability of cross-fostering to modulate the alterations in ER α expression secondary to variations in maternal care | Long-Evans hooded rats High vs Low LG ABN | Cross fostering within 12 h of birth | PND 90 | MPOA ER α mRNA exp | Cross fostering to high-care dam \uparrow ER α mRNA exp in Low LG ABN offspring to level of High LG ABN offspring | Cross fostering to High LG ABN dam reverses decreased ER α mRNA expression in offspring of Low LG ABN Long Evans dams on PND 90 |
| 75 | <i>Modulation of early stress-induced changes by simulated maternal grooming</i> Determine the ability of SMG to modulate MS-induced changes | Lewis rats MS from PNDs 1 to 28 for 2 h EAE induction at 14 weeks of age | SMG \sim 15 strokes for 30 s immediately following MS on PNDs 1–28 | 11 and 12 weeks | Hole board—11 weeks of age OFT—12 weeks of age Plasma CORT IL4, IL10 and IFN γ | SMG reversed MS-induced anxiety behaviours and \uparrow plasma IL4 versus MS alone. Reversed MS-induced \uparrow time in outer zone of OFT Attenuated MS-induced \uparrow no. of rearing events Elevated MS-induced \uparrow EAE clinical score \leftrightarrow MS-induced \downarrow CORT \uparrow IL4 vs MS alone | SMG reversed MS-induced anxiety behaviours and \uparrow plasma IL4 versus MS alone. |
| 76 | Determine the ability of SMG to modulate MS-induced hyperalgesia | Lewis rats MS from PNDs 1–27 for 2 h | SMG from PNDs 1 to 27; 15 short, heavy strokes on head and back for 30 s immediately following MS | PNDs 80 and 100 | Hot-plate testing—PND 80 Tail flick test—PND 100 | Attenuated MS-induced \downarrow hot plate latency \leftrightarrow MS-induced \downarrow tail flick latency | SMG in infancy modulated MS-induced hyperalgesia Lewis rats on PNDs 80 and 100 |
| 77 | <i>Modulation of early stress-induced changes by mixed housing</i> Determine the ability of mixed housing to modulate MS-induced changes in behaviour, CRH and OXT mRNA expression | M Sprague Dawley rats MS from PNDs 2 to 14 for 3 h | Altered housing conditions ^a Additional stress-chronic homotypic stress—for 90 min daily for 5 days after EPM | 8 and 9 weeks | EPM PVN CRH mRNA exp CRH ir OXT mRNA exp | MH (before CHS) Attenuated MS-induced \downarrow in open arm time in EPM Reversed MS-induced \downarrow total arm entries in EPM Reversed \downarrow duration of rearing behaviour After CHS, MH Reversed MS-induced \uparrow CRH mRNA exp MH reversed MS-induced \uparrow CRH ir MH reversed MS-induced \downarrow OXT mRNA exp | Mixed housing reversed MS-induced changes in anxiety behaviours, CRH and OXT mRNA expression in 8–9-week-old Sprague Dawley rats |

Abbreviations: \uparrow , increased; \downarrow , decreased; \leftrightarrow , no change; CHS, chronic, homotypic stress; CRH, corticotropin-releasing hormone; EAE, experimental autoimmune encephalomyelitis; EPM, elevated plus maze; ER, oestrogen receptor; exp, expression; IL, interleukin; IFN, interferon; ir, immunoreactivity; LG ABN, licking grooming arch back nursing; M, male; MH, mixed housing; MPOA, medial preoptic area; mRNA, messenger RNA; MS, maternal separation; OFT, open field test; OXT, oxytocin; PND, post-natal day; PVN, paraventricular nucleus; SMG, simulated maternal grooming. ^aAltered housing conditions: after weaning, rats were housed as either (1) pure MS: 3 MS rats were housed together, (2) mixed MS: 1 MS rat was housed with 2 NMS rats or (3) control: 3 NMS rats housed together.

marker, has been reported in the prefrontal cortex following maternal separation, with reductions correlated with the expression of depression-like behaviour.⁶⁰

BEHAVIOURAL INTERVENTIONS MODULATE EARLY STRESS-INDUCED CHANGES IN NEUROBIOLOGY

Offspring of low-care dams display lower levels of oestrogen receptor α (ER α) expression in the medial preoptic area (MPOA) compared with those raised by high-care dams.⁶¹ In the hippocampus, reduced glucocorticoid receptor (GR) expression and enhanced anxiety⁶¹ and depression-like⁶² behaviours have similarly been reported in offspring of low- versus high-care dams, suggesting early stress exerts its influence across a number of different brain regions. Cross-fostering (CF) of Long Evans hooded rats from low- to high-care dams within 12 h of birth has been shown to increase ER α expression in the MPOA of offspring on PND 90,⁶³ indicating that enhanced levels of maternal care can influence ER α expression. Maternal behaviour is facilitated by the expression of the oxytocin receptor (OXTR) in the MPOA,^{64–66} whose expression is ER α -dependent.¹³ In animal models, oxytocin has been shown to have a role in modulation of the neuroendocrine stress axis,^{67–70} the expression of anxiety-like behaviour⁷¹ and pain perception.^{72,73} Alterations in OXTR expression secondary to variations in maternal care may therefore influence the stress axis, behaviour and pain perception.

Sprague Dawley rats exposed to stroking on PND 10 exhibit enhanced oxytocin concentrations in the hypothalamus compared with non-stroked controls,⁷⁴ prompting investigation into the ability of simulated maternal grooming (SMG) to modulate behavioural changes induced by maternal separation. SMG, the application of short, heavy strokes on the head and back for 3 s immediately following maternal separation for the first month of life reversed separation-induced anxiety behaviours in Lewis rats in adulthood.⁷⁵ Serum corticosterone concentrations were unaltered by maternal separation,⁷⁵ preventing characterisation of the influence SMG exerted on the neuroendocrine stress response, however indicating that SMG did not exert its beneficial effect by modulating neuroendocrine activity. Attenuation of separation-induced hyperalgesia has also been reported following SMG from PNDs 1 to 27, as indicated by increased hot-plate latencies in SMG-treated Wistar rats compared with control.⁷⁶ Similarities exist between the influence SMG exerted over the stress axis and pain perception and the role of oxytocin within the brain. As such, it may be that SMG exerted its modulatory effect via influencing central oxytocinergic signalling, although oxytocin concentrations were not quantified in this study.⁷⁶

Mixed housing (MH) involves communal housing of separated and non-separated animals in the same cage from the time of weaning, and has been shown to attenuate enhanced anxiety behaviours following maternal separation in male Sprague Dawley rats.⁷⁷ Following administration of chronic homotypic stress, MH also reversed the increased CRH mRNA expression and immunoreactivity in the hypothalamus induced by early stress at 8–9 weeks of age.⁷⁷ Similar reversal of stress-induced changes in hypothalamic oxytocin mRNA expression was also noted in separated rats housed in mixed conditions.⁷⁷ Together these findings suggest that MH may exert its modulatory effect on behaviour by reducing CRH and enhancing oxytocin expression within the hypothalamus, thereby decreasing the magnitude of the HPA response to subsequent stress.

Whilst SMG and MH differ in specifics, each centres on enhancing the level of care provided during childhood. The similarities between the modulatory effects of these interventions with the roles of oxytocin within the central nervous system, including in the expression of maternal behaviour, suggest that these interventions may act *via* enhancing oxytocin signalling within the brain. Additional studies are required to quantify

central oxytocin and OXTR expression levels in response to such interventions to ascertain whether these behavioural interventions influence oxytocin expression in animal models of early stress (Table 1).

EXERCISE MODULATES EARLY STRESS-INDUCED CHANGES

Evidence is beginning to emerge indicating that exercise may have an important role in the prevention and treatment of psychiatric disorders⁷⁸ and may attenuate age-related cognitive decline.⁷⁹ This is of interest given the association between early life stress and the development of disorders such as depression later in life. Enhanced neuroplasticity has been shown in response to exercise, with changes often dependent on the type of exercise performed. Aerobic and resistance training have recently been reported to increase neuroplasticity to a greater extent compared with other subtypes of exercise.⁸⁰ Results from a meta-analysis indicate that exercise can improve cognitive performance in older adults (0.5 s.d. on average), irrespective of the nature of cognitive task, type of exercise or participant characteristics.⁷⁹ Taken together, findings suggest that enhanced neuroplasticity may be associated with functional improvement.

Exercise from PNDs 25 to 68 attenuated the increased immobility times in the forced swim test (FST) displayed by maternally separated Sprague Dawley rats compared with control from PND 26,⁸¹ suggesting reduced depression-like behaviour following intervention. The modulatory influence of exercise also appears to extend to other behaviours influenced by early stress in animal models. Maternally separated Sprague Dawley rats exercised from PNDs 21 to 30 exhibited improved long-term memory capability and spatial learning, as indicated by improved performance in the step-down latency and radial arm maze tasks compared with their non-exercised counterparts.⁸² Reports indicate that early stress can suppress the serotonin system^{83,84} and the role serotonin has in modulation of neural stabilisation and behavioural impairment.⁸⁵ While not a modulatory effect *per se*, exercise also enhanced serotonin synthesis and tryptophan expression in the hippocampus and dorsal raphe nuclei in both separated and non-separated Sprague Dawley rats⁸² alongside behavioural changes. Taken together, modulation of both serotonin expression and behaviour by exercise suggests that the positive influence exercise exerts may be partially attributable to its ability to alter the serotonergic system and the role it has in neural connectivity and behaviour.

Additional insight into the mechanisms by which exercise exerts its beneficial effect over early stress-induced changes in neurobiology comes from research examining modulation of cellular changes following maternal separation. Sprague Dawley rats exercised over a 6-week period in adulthood (from PNDs 40 to 82) following maternal separation from PNDs 2 to 14 exhibited reversal of changes in 16 of 23 proteins induced by maternal separation, including those involved in neuronal structure, signalling, neurotransmission and anti-oxidative stress.⁸⁶ Exercise was also reported to reduce the susceptibility of neurons to cell death previously increased by separation.⁸⁶ Treadmill exercise has also been shown to enhance synaptophysin and CamKII protein expression in the ventral hippocampus of both separated and non-separated Sprague Dawley rats on PND 65.⁸⁷ No differences in protein expression were noted in the dorsal hippocampus or prefrontal cortex in exercised versus non-exercised (both stressed and non-stressed),⁸⁷ indicating that the effect of exercise may in fact be brain-region-specific.

Evidently, exercise modulates a number of cellular changes (such as changes in proteins involved in neuronal structure, neurotransmission, and oxidative stress and cell death) that result from early stress, indicating that it likely exerts its beneficial influence on behaviour (including depression-like behaviour, spatial learning and memory, and long-term memory capability)

via a number of intertwined mechanisms. Considered together with its ability to modulate behavioural changes induced by early stress, it may be that exercise modulates the negative influence early stress exerts on behaviour and the later predisposition to disease by attenuating the impact childhood stress exerts on the developing brain at a structural level, potentially within the hippocampus, given that a number of behaviours modulated by exercise are known to be hippocampal-dependent.

EARLY STRESS-INDUCED CHANGES CAN BE MODULATED BY ENVIRONMENTAL ENRICHMENT

Improved dendritic arborisation, neurogenesis, synaptogenesis and long-term potentiation have been reported following EE in animal models.^{88,89} EE has recently been hypothesised to prevent some of the deleterious effects of stress exposure.^{90–92} However, only one study has addressed the ability of EE to modulate neurobiological changes induced by maternal separation to date. EE involved housing Wistar rats in groups of 7–10 in cages containing toys, wooden blocks, climbing platforms and running wheels.⁹³ Maternally separated rats raised under conditions of EE displayed reversal of separation-induced decreases in grooming behaviour in the open field test, and attenuation of separation-induced impairments in the step-down test.⁹³ Findings from the step-down test indicate that early stress induced a deficit in memory acquisition, consolidation or retrieval, and that this was reversed by EE. At this stage it is unknown as to exactly how EE alters behavioural changes that result from early stress, however it is known to enhance neuroplasticity on a structural level.⁹³ Findings from animal studies indicate that EE results in functional enhancement of neurophysiology and memory, while increasing dendritic arborisation, neurogenesis, synaptogenesis and long-term potentiation.^{88,89} As such, EE may modulate memory deficits induced by maternal separation by 'reprogramming' some of these same circuits in response to the enriched environment, thereby attenuating the influence early separation exerts on memory. It would be of interest for further studies to assess the ability of EE to modulate other behaviours known to be adversely affected by early stress such as anxiety and depression-like behaviours (Table 2).

PHARMACOLOGICAL INTERVENTIONS CAN MODULATE THE NEUROBIOLOGICAL SEQUELAE OF EARLY STRESS

The endocannabinoid system has an imperative role in key neurodevelopmental processes such as cell proliferation, migration and differentiation, axonal elongation and synaptogenesis.^{96–99} It is also considered to function as a crucial regulator of the neuroendocrine stress response.¹⁰⁰ Recent evidence also suggests that the endocannabinoid system serves as a homeostatic neuroprotective mechanism, counteracting diverse neural insults.⁴⁹ For example, administration of WIN-55, a cannabinoid agonist, has been shown to reduce neuronal loss in neonatal rats following severe asphyxia.¹⁰¹ Similarly, modulation of the endocannabinoid system has been shown to decrease behavioural impulsivity following maternal deprivation in adolescent rats.¹⁰²

Two endocannabinoid system enhancers, arachidonoyl serotonin (AA-5HT) and OMDM-2 have been shown to modulate cellular changes within the CA1 and CA3 of the hippocampus following maternal deprivation,¹⁰³ an area proposed to have a key role in mediating the behavioural effects of endocannabinoids.¹⁰⁴ Administration of AA-5HT and OMDM-2 from PNDs 7 to 12 reduced deprivation-induced increases in glial fibrillary acidic protein (GFAP) expressed by astrocytes in Wistar rats on PND 13 compared with control.¹⁰³ Attenuation of elevations in plasma corticosterone concentrations secondary to deprivation were also reported in treated male Wistar rats versus control,¹⁰³ suggesting

that raised corticosterone may have influenced cellular changes in the hippocampus of the male rat, and that both AA-5HT and OMDM-2 acted to reduce these changes. Similar findings have been reported in the cerebellum of maternally deprived Wistar rats, with female Wistar rats treated with AA-5HT or OMDM-2 displaying reduced numbers of GFAP-positive cells compared with their non-treated counterparts.¹⁰⁵ The influence of early stress on FJC-positive cells, indicative of degenerating neuron numbers, in the cerebellum was also attenuated in male rats given AA5-HT or OMDM-2, while expression was unchanged in females.¹⁰⁵ When considered together, it appears that the endocannabinoid system enhancers AA-5HT and OMDM-2 reduce the influence maternal deprivation exerts on cellular changes within the brain in a sex-dependent manner in both the hippocampus and cerebellum, possibly via altering neuroendocrine function.

To date, only one study has addressed the ability of endocannabinoid system modulators to alter behavioural changes induced by early stress. URB597 is a selective inhibitor of the enzyme fatty acid amide hydrolase, which is responsible for the breakdown of the endocannabinoid anandamide.¹⁰² Administration of URB597 from PNDs 31 to 43 results in attenuation of increases in behavioural impulsivity displayed by maternally deprived Wistar rats,¹⁰² suggesting that enhancing endocannabinoid signalling can exert beneficial effects on behaviour.

ANTI-INFLAMMATORIES MODULATE EARLY STRESS-INDUCED CHANGES

Dysfunction or loss of γ -aminobutyric acid-ergic (GABA) cells that express parvalbumin, a calcium-binding protein, have been implicated in the aetiopathogenesis of a variety of psychiatric conditions.^{106–108} Reduced parvalbumin expression has been reported in Sprague Dawley rats maternally separated from PNDs 2 to 20.¹⁰⁹ Administration of the cyclo-oxygenase 2 (COX-2) inhibitor (NS398), a key mediator of both oxidative stress and excitotoxicity, attenuated decreases in parvalbumin expression in the prefrontal cortex of separated rats compared with vehicle-treated rats upon assessment in adolescence.¹¹⁰ Moreover, improved working memory previously impaired by maternal separation was also reported in rats treated with NS398, as indicated by reduced errors in the win-shift maze task.¹¹⁰ NS398 is reported to have neuroprotective effects, and to exert a modulatory influence over excitotoxicity and neuroinflammatory insults^{111–113} potentially by reducing the conversion of arachidonic acid to prostaglandin, thereby reducing the multifaceted downstream effects of prostaglandins (such as induction of inflammatory mediators causing neuronal damage,¹¹⁴ aggravation of excitotoxic neurodegeneration¹¹⁵ or induction of apoptosis via stimulation of astrocytes to release glutamate¹¹⁶). As a possible mechanism of action, it can be speculated that the effects of NS398 on parvalbumin expression may therefore have been via attenuation of inflammatory changes induced by early stress, although inflammatory markers were not quantified directly in this study. In support of these suggestions is the observation that separation-induced decreases in parvalbumin expression are attenuated by the intracerebroventricular administration of the anti-inflammatory interleukin (IL) 10.¹¹⁷ Moreover, a linear relationship between IL6 and parvalbumin expression in the prefrontal cortex was reported in separated rats treated with IL10,¹¹⁷ suggesting that the enhanced pro-inflammatory activity that persists after early stress leads to decreased parvalbumin expression in the prefrontal cortex, potentially altering the predisposition to psychiatric disease.

Table 2. Environmental enrichment modulates early stress-induced changes

| Reference | Objective | Early stress | Intervention | Assessment age | Outcome measures | Results | Interpretation |
|-----------|---|--|---|---|---|--|---|
| 82 | Modulation of early stress-induced changes by exercise Determine the ability of exercise to modulate MS-induced changes | Sprague Dawley rats MS from PNDs 2 to 14 | Forced treadmill exercise for 30 min per day on PNDs 21–30 | Behavioural tests PND 27 Molecular assessment PND 35 | Step-down avoidance task Radial arm maze task Dorsal raphe nuclei 5-HT synthesis and TPH exp Hippocampus Apoptotic neuronal cell death (TUNEL+ cells) Cell proliferation Ventral hippocampus Protein exp | Exercise Attenuated MS-induced step-down latency and ↑ RAMT completion time Attenuated MS-induced ↑ TUNEL+ cells and ↑ caspase 3 exp ↑ cell proliferation, 5-HT synthesis and TPH exp in MS and NMS | Exercise modulated MS-induced behavioural changes and reduced neuronal cell death in Sprague Dawley rats from PND 27 |
| 86 | Determine the ability of exercise to modulate MS-induced changes in protein expression | M Sprague Dawley rats MS from PNDs 2 to 14 for 3 h | Voluntary treadmill exercise during dark hours, 5 days per week on PNDs 40–82 | PND 83 | OFT and EPM—PND 49 MWM—PND 50–55 ORT—PND 63 | Exercise Reversed exp of 16 of 23 proteins changed by MS ^a | Exercise modulated the MS-induced changes in protein expression and ↑ susceptibility of neurons to cell death in M Sprague Dawley rats on PND 83 MS did not induce behavioural changes |
| 94 | Determine the ability of exercise to modulate MS-induced changes in behaviour | Sprague Dawley rats MS from PNDs 2 to 14 for 3 h | Voluntary unlimited treadmill exercise on PNDs 29–49 | PNDs 49–63 | | MS ↔ OFT, EPM, MWM or ORT Exercise ↓ locomotor activity in OFT ↓ time in open arm in EPM ↓ latency to locate platform in MWM | MS did not induce behavioural changes |
| 81 | Determine the ability of exercise to modulate MS-induced changes in behaviour | Sprague Dawley rats MS from PNDs 2 to 14 for 1 h | Voluntary treadmill exercise for 1 h per day, 5 days per week on PNDs 26–68 | From PND 26 | FST Light/dark box test Short-time treadmill test | Exercise Attenuated MS-induced ↑ immobility in FST and ↓ time in light box | Exercise modulated MS-induced depression and anxiety-like behaviour in Sprague Dawley rats from PND 26 |
| 87 | Determine the ability of exercise to modulate MS-induced changes in synaptic plasticity | Sprague Dawley rats MS from PNDs 2 to 14 for 3 h | Voluntary unlimited treadmill exercise on PNDs 29–49 | PND 65 | Ventral hippocampus Synaptophysin protein exp CaMKII protein exp | Exercise ↑ synaptophysin and CaMKII exp in MS and NMS | Exercise ↑ synaptophysin and CaMKII exp in the hippocampus of MS and NMS Sprague Dawley rats on PND 65 |
| 95 | Modulation of early stress-induced changes by other forms of environmental enrichment Determine the ability of CCL treatment in adolescence to modulate MS-induced behavioural and molecular changes | Sprague Dawley rats MS from PNDs 2 to 14 for 3 h | Chronic constant light ^b from PNDs 42 to 63 | USV—PND 65 FST—PND 66 Molecular—PND 101 | USV BDNF exp (hippocampus) Mu opioid R exp (nucleus accumbens) | CCL Reversed MS-induced ↑ USV Reversed MS-induced ↑ immobility in FST Reversed MS-induced ↓ in mu opioid r exp ↔ on MS-induced ↑ BDNF EE Reversed MS-induced ↓ grooming in OFT Reversed MS-induced ↓ step-down latency | CCL reversed MS-induced changes in USV, depression-like behaviour and mu opioid receptor expression |
| 93 | Determine the ability of EE during adolescence to modulate MS-induced changes in behaviour | Wistar rats MS from PNDs 1 to 21 for 4.5 h | Environmental enrichment ^c from PNDs 21 to 60 | PNDs 67–74 | OFT NORT Step-down inhibitory avoidance | EE Reversed MS-induced ↓ grooming in OFT Reversed MS-induced ↓ step-down latency | EE reversed MS-induced deficits in memory acquisition, consolidation or retrieval |

Table 2. (Continued)

| Reference | Objective | Early stress | Intervention | Assessment age | Outcome measures | Results | Interpretation |
|-----------|-----------|--------------|--------------|----------------|------------------|---|----------------|
| | | | | | | Attenuated MS-induced ↓ in freezing behaviour in step-down test | |

Abbreviations: ↑, increased; ↓, decreased; ↔, no change; 5-HT, serotonin; BDNF, brain-derived neurotrophic factor; CaMKII, calcium/calmodulin-dependent protein kinase; CCL, chronic constant light; EE, environmental enrichment; EPM, elevated plus maze; exp, expression; FST, forced swim test; M, male; MS, maternal separation; MWM, morris water maze; NMS, non-maternal separation; NORT, novel object recognition test; OFT, open field test; ORT, object recognition test; PFC, prefrontal cortex; PND, post-natal day; R, receptor; RAMT, radial arm maze task; TPH, tryptophan; USV, ultrasonic vocalisations. ^aStructural proteins: tau, tubulin alpha-1B, actin; proteins involved in energy metabolism: creatine kinase B, malate dehydrogenase; proteins involved in oxidative stress: heat shock cognate 71 kDa, polyubiquitin; proteins involved in neuronal survival and plasticity: γ-enolase, acidic (leucinerich) nuclear phosphoprotein 32 family member A, high-mobility group box 1; proteins involved in apoptosis and calcium signalling: peptidyl-prolyl cis-trans isomerase, PPIase FKBP1A, calmodulin; proteins involved in protein metabolism: transmembrane protease serine 13, phosphatidylethanolamine-binding protein 1, plasminogen activator inhibitor 1 RNA-binding protein. ^bRats were placed under lighting of relatively low irradiance (100–120 l) at the floor of the cage (generated by a 40-W clear bulb). ^cRats were housed in groups of 7–10 and housed in an enriched environment. Cages contained toys, wooden blocks, climbing platforms, running wheels and plastic tubes.

MODULATION OF EARLY STRESS-INDUCED CHANGES THROUGH ANTIDEPRESSANT ADMINISTRATION

Animal models illustrate that monoaminergic neurons such as those containing serotonin and noradrenaline are susceptible to perturbations in the early environment.¹¹⁸ Both serotonergic and noreadrenergic neurons are known to have critical roles in stress-related behaviours and disorders;^{109,119,120} the development of psychiatric disorders such as anxiety and depressive disorders has been linked to changes in the density of these neurons.^{121–124}

Tricyclic antidepressants

Initial studies focusing on the ability of monoaminergic-modulating drugs to alter neurobiological changes induced by early adversity centred on the use of tricyclic antidepressants (TCAs). Complete reversal of maternal separation-induced anxiety behaviours was reported in Lewis rats treated with imipramine from adolescence into adulthood.⁷⁵ The authors also demonstrated attenuation of changes in experimental autoimmune encephalomyelitis clinical scores following imipramine administration.⁷⁵ Similar reductions in hyperalgesia induced by maternal separation were noted in a subsequent study by this group, as indicated by improved hot-plate latencies in imipramine versus vehicle-treated rats in adulthood.⁷⁶

Desipramine also appears to exert a beneficial influence over behavioural changes induced by early stress. Reduced immobility times in the FST have been shown in maternally separated Sprague Dawley rats treated with desipramine compared with vehicle-treated rats from PND 21,⁸¹ suggesting reduced depression-like behaviours in those given desipramine. Anxiety-like behaviour was unaltered by desipramine,⁸¹ suggesting that its modulatory effect may be behaviour-dependent. Although speculative, it may be that desipramine exerts a greater influence over the hippocampus than over the amygdala, thereby altering depression but not anxiety-like behaviours that result from early stress. It would be of use to investigate this further in future models. Transmission of depression-like behaviour from maternally separated male C57BL/6 mice to their female offspring has recently been demonstrated. Adult male C57BL/6 mice maternally separated (and that displayed enhanced depression-like behaviours) as pups were bred with control females. Offspring were treated with desipramine in childhood. Compared with those treated with the vehicle, female offspring treated with desipramine displayed attenuation of depression-like behaviours in the FST.¹²⁵ In contrast, desipramine administration to female offspring in adulthood did not influence depression-like behaviour,¹²⁵ indicating that transgenerational transmission of depression-like behaviours are only amenable to intervention during the early post-natal period. When considered together, these studies indicate that enhanced depression-like behaviour following maternal separation, and even transgenerational transmission of these behaviours, are amenable to intervention with desipramine.

Selective serotonin reuptake inhibitors

In addition to work focusing on the modulatory effect TCAs exert on alterations induced by early adversity, a number of studies have centred on the ability of selective serotonin reuptake inhibitors (SSRIs) to alter changes that result from early stress. Maternally separated Sprague Dawley rats treated with fluoxetine in adolescence were reported to exhibit attenuation of decreases in step-down latency and increases in radial arm maze completion time compared with those treated with the vehicle.⁸² From a molecular perspective, this study showed that fluoxetine reduced the influence separation exerted on neuronal apoptosis in the hippocampus, while enhancing hippocampal cell proliferation on PND 35.⁸² As such, it is likely that fluoxetine enhanced long-term memory capability and spatial learning via increasing cell

Table 3. Antidepressants modulate early stress-induced changes

| Reference | Objective | Early stress | Intervention | Assessment age | Outcome measures | Results | Interpretation |
|-----------|--|---|--|--|--|---|--|
| 132 | <p><i>Modulation of early stress-induced changes by TCA administration</i></p> <p>Determine the ability of amytryptiline to modulate MS-induced changes in neuroendocrine activity</p> | <p>M Wistar rats MS from PND 1 to 21 for 4.5 h</p> | <p>Amytryptiline (5 mg kg⁻¹) from PNDs 50 to 74 (at the same times chronic variable stress)</p> | PND 75 | Plasma CORT and ACTH | <p>Amytryptiline Attenuated MS-induced ↑ CORT</p> <p>Reversed MS+CVS-induced ↑ CORT ↔ on MS-induced ↓ ACTH</p> <p>↔ on MS+CVS-induced ↑ ACTH (vs MS only)</p> | <p>Amytryptiline modulated MS-induced changes in corticosterone under basal and stress-induced conditions, but did not alter ACTH concentrations</p> |
| 125 | <p>Determine the ability of desipramine to modulate MS-induced changes in behaviour</p> | <p>C57/BL6 mice Unpredictable MS from PND 1–14 for 3 h</p> | <p>Acute or chronic desipramine IP^a</p> | <p>Adulthood 3–8 months, 1–2 weeks between tests</p> | FST | <p>MS ↑ floating in FST in M</p> <p>MS ↑ immobility in tail suspension in M F2</p> <p>MS offspring ↑ floating in FST in F</p> <p>MS offspring ↑ immobility in tail suspension in F</p> <p>Desipramine Reversed ↑ floating and immobility times in F</p> | <p>Desipramine modulated MS-induced depression-like behaviour in adult F2 C57/BL6 offspring</p> |
| 81 | <p>Determine the ability of desipramine to modulate MS-induced changes in behaviour</p> | <p>Sprague Dawley rats MS from PND 2 to 14 for 1 h</p> | <p>Desipramine 10 mg kg⁻¹ per day IP on PND 21–42</p> | From PND 26 | <p>FST</p> <p>Light/dark box test</p> <p>Short-time treadmill test</p> | <p>Desipramine Attenuated MS-induced ↑ immobility in FST</p> <p>↔ light box</p> <p>↔ locomotion in MS and NMS</p> | <p>Desipramine modulated MS-induced depression and anxiety-like behaviour in Sprague Dawley rats from PND 26</p> |
| 117 | <p>Determine the ability of clomipramine to modulate MS-induced behaviour and 5-HT and DBH axon density</p> | <p>M Sprague Dawley rats Isolated vs group reared from PND 28</p> | <p>Clomipramine 22.5 mg kg⁻¹ 2 × daily SC on PND 8–21</p> | <p>OFT—PND 49</p> <p>FST—PND 56/7 or 65/6</p> <p>5-HT/DBH PND 69 or 73</p> | <p>OFT</p> <p>FST</p> <p>CA3, BLA and CeA</p> <p>5-HT & DBH axon density</p> | <p>↔ isolation or clomipramine in OFT</p> <p>Clomipramine ↔ isolation induced immobility in FST</p> <p>↔ isolation induced 5-HT and DBH+ axon density</p> | <p>Clomipramine did not alter isolation induced changes in depression-like behaviour or 5-HT and DBH+ axon density in M Sprague Dawley rats in adulthood</p> |
| 133 | <p>Determine the ability of nortriptyline to modulate MS-induced changes in depression-like behaviour</p> | <p>M FSL rats</p> <p>M FRL rats</p> <p>MS from PND 2–14</p> | <p>Nortriptyline 25 mg kg⁻¹ per day in chow on PND 42–73</p> | PND 66 | FST | <p>FSL ↑ immobility vs FRL</p> <p>Nortriptyline ↓ immobility in FSL</p> <p>MS ↔ immobility in FST</p> <p>Nortriptyline ↔ immobility in MS</p> <p>Imipramine Reversed MS-induced ↑ time in outer zone</p> | <p>MS did not induce behavioural changes</p> |
| 75 | <p>Determine the ability of imipramine to modulate MS-induced changes</p> | <p>Lewis rats MS from PND 1 to 28 for 2 h</p> | <p>Imipramine 10 mg kg⁻¹ PO from 6 weeks age</p> | 11 and 12 weeks | <p>Hole board—11 weeks age</p> <p>OFT—12 weeks age</p> | <p>Imipramine Reversed MS-induced ↑ time in outer zone</p> | <p>Imipramine reversed MS-induced anxiety behaviours and ↑ plasma IL4 versus MS alone.</p> |

Table 3. (Continued)

| Reference | Objective | Early stress | Intervention | Assessment age | Outcome measures | Results | Interpretation |
|--|--|---|--|---|--|--|---|
| | | EAE induction at 14 weeks of age | | | Plasma CORT IL4, IL10 and IFN γ | of OFT Elevated MS-induced \uparrow no. of rearing events Attenuated MS-induced \uparrow EAE clinical score \leftrightarrow MS-induced \downarrow CORT \uparrow IFN γ and IL4 vs MS alone | Imipramine also \uparrow plasma IFN γ in 11–12-week-old Lewis rats |
| 76 | Determine the ability of imipramine to modulate MS-induced hyperalgesia | Lewis rats MS from PNDs 1 to 27 for 2 h | Imipramine 10 mg kg $^{-1}$ per day PO from 8–16 weeks age | PNDs 80 and 100 | Hot-plate testing—PND 80 Tail flick test—PND 100 | Imipramine Attenuated MS-induced \downarrow hot plate latency and \downarrow tail flick latency | Chronic imipramine administration in adolescence modulated MS-induced hyperalgesia Lewis rats on PNDs 80 and 100 |
| <i>Modulation of early stress-induced changes by SSRI administration</i> | | | | | | | |
| 82 | Determine the ability of fluoxetine to modulate MS-induced changes | Sprague Dawley rats MS from PND 14 | Fluoxetine 5 mg kg $^{-1}$ SC on PNDs 21–30 | Behavioural tests PND 27 Molecular assessment PND 35 | Step-down avoidance task Radial arm maze task Dorsal raphe nuclei 5-HT synthesis and TPH exp Hippocampus Apoptotic neuronal cell death (TUNEL+ cells) Cell proliferation | Fluoxetine Attenuated MS-induced \downarrow step-down latency and \uparrow RAMT completion time Attenuated MS-induced \uparrow TUNEL+ cells and \uparrow caspase 3 exp \uparrow cell proliferation in MS \uparrow 5-HT synthesis and TPH exp in MS and NMS | Fluoxetine modulated MS-induced behavioural changes and reduced neuronal cell death in Sprague Dawley rats from PND 27 |
| 129 | Determine the ability of escitalopram to modulate MS-induced changes in cognition | M Wistar rats MS from PNDs 2 to 14 for 3 h | Escitalopram (0.34 mg kg $^{-1}$ per day for first 2 weeks; 0.41 mg kg $^{-1}$ per day for next 2 weeks) | FST PNDs 64–65 MWM PNDs 80–84 | FST MWM | Escitalopram Attenuated MS-induced \downarrow latency to despair in FST Improved immobility in FST in MS and NMS Attenuated MS-induced \downarrow time in target quadrant during probe trial in MWM | Escitalopram in adulthood improved MS-induced impairments in hippocampal-dependent memory and latency to despair |
| 25 | Determine the ability of escitalopram to modulate MS-induced changes in neurometabolites | Sprague Dawley rats MS from PNDs 2 to 14 for 3 h | Escitalopram oxalate 10 mg mg kg $^{-1}$ by gavage on PNDs 43–60 | PNDs 70–75 | Hippocampal volume (MRI) L and R hippocampi NAA/Cr ratio Glu/Cr ratio MI/Cr ratio Cho/Cr ratio | \leftrightarrow MS or escitalopram on hippocampal volume Escitalopram Attenuated MS-induced \downarrow NAA/Cr, MI/Cr ratios in L and R hippocampi Attenuated MS- | Escitalopram reversed the MS-induced \downarrow in the neurometabolites NAA/Cr, Glu/Cr and MI/Cr in Sprague Dawley rats on PND 75 |

Table 3. (Continued)

| Reference | Objective | Early stress | Intervention | Assessment age | Outcome measures | Results | Interpretation |
|---|---|--|--|---|---|--|---|
| 127 | Determine the ability of fluoxetine, ketamine and ECT to modulate MS-induced changes in mGluR mRNA levels | Sprague Dawley rats MS for 3 h from PNDs 2 to 12 | 1 of 3 antidepressant treatments ^a | 24 h after final antidepressant treatment | Hippocampus mGlu4 receptor mGlu7 receptor mGlu8 receptor | induced ↓ Glu/Cr ratio in R hippocampus Fluoxetine Reversed MS-induced ↓ mGlu4 exp ECT and ketamine ↔ mGlu4 exp MS ↔ mGlu7 or mGlu8 exp | Fluoxetine reversed MS-induced changes in mGlu4 expression; ECT and ketamine did not modulate changes in mGlu4 expression |
| 134 | Determine the ability of escitalopram to modulate MS-induced changes in depression-like behaviour | M FSL rats M FRL rats MS from PNDs 2 to 14 for 3 h | Escitalopram 25 mg kg ⁻¹ per day in chow on PNDs 41 to 72 | PND 62 | FST | FSL ↑ immobility vs FRL Escitalopram ↓ immobility in FSL MS ↔ immobility Escitalopram ↔ immobility in MS | MS did not induce behavioural changes |
| 126 | Determine the ability of fluoxetine to modulate MS-induced changes in behaviour and serotonin expression in the brain | F Sprague Dawley rats MS from PNDs 1 to 14 for 3 h | Fluoxetine from PND 35 (10 mg kg ⁻¹) until assessment age | Behaviour—PNDs 44–54 Neurochemical analysis—PNDs 43–45 | Locomotor activity FST EPM mRNA exp CRH exp Plasma CORT | In MS rats, fluoxetine attenuated MS-induced ↓ 5-HT in raphe nucleus In MS & NMS rats, fluoxetine ↓ time in open arms, ↑ time in closed arms in both MS and NMS ↑ 5-HT and its metabolite 5-HIAA in hypothalamus in MS and NMS | Fluoxetine attenuated MS-induced decreases in serotonin expression in the raphe nucleus |
| <i>Modulation of early stress-induced changes by lithium administration</i> | | | | | | | |
| 135 | Determine the ability of lithium to modulate MS-induced changes in NPY and CRH immunoreactivity | Sprague Dawley rats MS from PNDs 2 to 14 for 3 h | Lithium on PNDs 50–83 (17.5 mmol kg ⁻¹ chow for 7 days; then 25 mmol kg ⁻¹ thereafter) | PND 83 | Hippocampus and hypothalamus NPY-like ir CRH-like ir NPY-ir/CRH ir ratio | Lithium Attenuated MS-induced ↓ NPY-ir in hippocampus Enhanced MS-induced ↑ NPY-ir in hypothalamus ↑ CRH ir in hippocampus in MS & NMS ↑ NPY-CRH ratio in MS and NMS | Lithium modulated MS-induced ↓ in NPY-ir in the hippocampus, but worsened this ↓ in the hypothalamus of Sprague Dawley rats on PND 83 |

Abbreviations: ↑, increased; ↓, decreased; ↔, no change; 5-HT, serotonin; 5-HTT, serotonin transporter; ACTH, adrenocorticotropic hormone; CeA, central nucleus of the amygdala; Cho, choline; CORT, corticosterone; Cr, creatine; CRH, corticotropin-releasing hormone; CVS, chronic variable stress; DBH, dopamine beta hydroxylase; EAE, experimental autoimmune encephalomyelitis; ECT, electroconvulsive therapy; EPM, elevated plus maze; exp, expression; F, female; FRL, flinders-resistant line; FS, flinders-sensitive line; FST, forced swim test; Glu, glutamate; IP, intraperitoneal; ir, immunoreactivity; L, left; M, male; mGluR, metabotropic glutamate receptor; Mi, myoinositol; mRNA, messenger ribonucleic acid; MS, maternal separation; MWM, Morris water maze; NMS, non-maternal separation; NPY, neuropeptide Y; OFT, open field test; PND, post-natal day; PO, per oral; R, right; SC, subcutaneous; TPH, tryptophan. ^aRats were administered 1 of 3 antidepressant treatments: (1) repeated ECT treatment (85 mA for 0.5 ms per day for 10 days) to induce a classic grand mal seizure lasting ~15 s, (2) acute ketamine treatment (a single dose of 10 mg kg⁻¹ in saline) or (3) chronic (21 day) fluoxetine treatment (10 mg kg⁻¹ per day in saline).

proliferation in the hippocampal dentate gyrus. Additionally, although not a modulatory effect, fluoxetine increased serotonin synthesis and tryptophan expression in the dorsal raphe nuclei in both separated and non-separated Sprague Dawley rats on PND 35.⁸² Others have reported similar modulation of the serotonergic system by fluoxetine following early stress. Female Sprague Dawley rats treated with fluoxetine from PND 35 displayed attenuation of maternal separation-induced reductions in serotonin expression in the raphe nucleus compared with control.¹²⁶ Fluoxetine has also been shown to reverse separation-induced changes in metabotropic glutamate receptor 4 (mGluR4) expression in the hippocampus of Sprague Dawley rats in a study comparing the efficacy of fluoxetine with electroconvulsive therapy and ketamine. Interestingly, neither electroconvulsive therapy nor ketamine administration altered changes in mGluR4 expression in these maternally separated rats.¹²⁷ As such, it may be hypothesised that fluoxetine exerts at least part of its therapeutic benefit by targeting group III mGlu receptors, thereby attenuating the reduction in mGluR4 receptors caused by early stress and preventing the decrease in negative feedback, which can ultimately lead to excessive glutamate release and hyperexcitability.

Escitalopram also appears to modulate cellular alterations induced by early stress. Decreased concentrations of the neurometabolites N-acetylaspartate, choline and myoinositol, indicative of reduced neural density and functional integrity, were noted in the hippocampus of Sprague Dawley rats following maternal separation.¹²⁸ These separation-induced changes in neurometabolite concentrations were attenuated significantly in escitalopram versus vehicle-treated rats in adulthood;¹²⁸ separated escitalopram-treated rats displayed higher concentrations of these neurometabolites compared with separated rats that received vehicle. Consistent with this, others have reported that escitalopram reduced depression-like behaviour that occurred after maternal separation in Wistar rats.¹²⁹ The mechanisms underlying the antidepressant effect of escitalopram are thought to be the result of either stimulation of neuronal remodelling in the hippocampus,¹³⁰ or via modulation of the HPA axis.¹³¹ Furthermore, in the same experiment, improved hippocampal-dependent memory in the probe trial of the Morris Water maze was demonstrated in escitalopram-treated rats, which is in line with the beneficial effects escitalopram exerts on separation-induced depression-like behaviours.¹²⁹

Considered together, works examining the modulatory influence of TCAs and SSRIs indicate that modulation of monoaminergic signalling acts to attenuate or reverse alterations in behaviour induced by early stress, in addition to a number of cellular changes. The specific mechanisms underlying the way in which antidepressants achieve these effects remain to be fully characterised. It may be hypothesised that TCAs and SSRIs attenuate deficits in monoaminergic signalling caused by early stress, thereby partially restoring their function and the role they have in the regulation of stress-related behaviours. Modulation of the HPA axis¹³¹ and neuronal remodelling¹³⁰ may also contribute to their effect on depression-like behaviours. Changes in memory capability following antidepressant administration may be the result of enhanced cell proliferation in the hippocampus.⁸² Clearly, the mechanisms underpinning these actions need to be further characterised in future models to ascertain at what level these drugs exert their influence (Table 3).

EPIGENETIC-MODIFYING DRUGS MODULATE EARLY STRESS-INDUCED CHANGES

The first studies assessing whether epigenetic changes induced by variations in the early environment were amenable to intervention centred on the use of methionine, a drug that enhances the methylation status of candidate genes. Generally, the methylation

status of a candidate gene is inversely correlated with the level of gene expression; low levels of gene methylation have generally been associated with increased gene expression to date.^{136,137}

Intracerebroventricular methionine administration from PNDs 97 to 103 in the offspring of high-care Long-Evans hooded dams has been shown to increase the methylation status of the nerve growth factor-inducible protein A (NGFI-A) consensus sequence of the exon 1₇ GR promoter to the level of offspring of low-care dams.¹³⁸ These results indicate that the influence of early environment on the epigenome are amenable to intervention in adulthood. A concomitant decrease in histone 3 lysine 9 (H3K9) in association with the exon 1₇ GR promoter and decreased GR mRNA and protein expression in the hippocampus of high-care offspring was also demonstrated, once again to the level of low-care offspring.¹³⁸ Such findings suggest that the changes in the epigenome modified by methionine administration were functionally relevant. Specifically, methionine administration in high-care offspring was shown to enhance anxiety⁶¹ and depression-like⁶² behaviour to the level of low-care offspring. Such results illustrate that epigenetic alterations are associated with behavioural changes, potentially via their influence on the HPA axis and stress responsivity, and that it is possible to modulate changes in behaviour through the administration of epigenetic-modifying drugs such as methionine in adulthood. Although these results are of little translational benefit as they worsen behavioural changes induced by early stress, the findings demonstrate the susceptibility of the epigenome to pharmacologic manipulation in adulthood.

Initial studies on methionine lead to investigation into the ability of the DNA methylation inhibitor zebularine to modulate changes in brain-derived neurotrophic factor (BDNF) expression induced by early stress.¹² Long Evans hooded rats exposed to abusive Long Evans mothers in childhood and treated with zebularine in adulthood (PNDs 83–89) displayed attenuation of stress-induced decreases in BDNF mRNA expression in the prefrontal cortex in adulthood compared with those that received vehicle.¹² These findings are of interest as they illustrate that differences in DNA methylation, specifically gene hypermethylation, induced by early stress can be reversed in adulthood.

Post-translational histone modifications represent another epigenetic mechanism that appears to be modulated by the early environment, and level of care received by offspring. The level of histone acetylation correlates positively with the level of gene expression.¹³⁹ Reduced histone acetylation therefore tends to result in decreased expression of a certain gene. Trichostatin A (TSA), a histone deacetylase inhibitor, reduces the rate of deacetylation of candidate genes, enhancing the level of histone acetylation and therefore gene expression. It has been shown that low levels of maternal care reduce histone acetylation in rat offspring, and result in decreased gene transcription and protein expression.¹³⁸ In addition, TSA administration (from PNDs 90 to 97) in low-care offspring has been shown to enhance GR mRNA expression in the hippocampus to the level of high-care Long Evans hooded offspring.¹³⁸ The authors extrapolated their findings in further work (utilising the same experimental design) demonstrating that TSA administration reduced anxiety-like behaviours of low-care offspring to the level of high-care offspring.⁶² Together, the results of this collection of works suggests that the adverse behavioural consequences associated with low levels of maternal care in early life are amenable to intervention in adulthood through histone deacetylase inhibitor administration.

Another histone deacetylase inhibitor, valproic acid, has been reported to attenuate decreases in acoustic startle in maternally separated female Sprague Dawley rats when administered during childhood.¹⁴⁰ Interestingly however, valproic acid only modulated behaviour when administered in the early post-natal period (PNDs 2–9); administration from PNDs 28 to 36 did not influence behaviour,¹⁴⁰ indicating that the ability of valproic acid to

Table 4. Epigenetic-modifying drugs modulate early stress-induced changes

| Reference | Objective | Early stress | Intervention | Assessment age | Outcome measures | Results | Interpretation |
|-----------|---|--|---|------------------------|---|--|---|
| 140 | Determine the ability of 5-AZA and valproic acid to modulate MS-induced changes in behaviour, histone acetylation and methylation | F Sprague Dawley rats MS from PNDs 2 to 9 for 1 h | Early or late 5-azadeoxycytidine inhibitor or valproic acid PO ^a | PND 42 | Acoustic startle Frontal cortex HistoneH3K9 methylation | Early valproic acid Attenuated MS-induced ↓ acoustic startle Attenuated MS-induced ↑ histone H3K9 mono and trimethylation Late valproic acid ↔ MS-induced changes 5-AZA ↔ MS-induced ↓ acetylation MS-induced ↑ acoustic startle | Early valproic acid modulated MS-induced ↓ acoustic startle and histone H3K9 mono and trimethylation in F Sprague Dawley rats on PND 42 |
| 141 | Determine the ability of theophylline and fluoxetine to modulate MS-induced changes in histone acetylation and methylation | Balb/c mice MS from PNDs 2 to 12 for 3 h | Theophylline 16 mg kg ⁻¹ per day in water on PNDs 35–60 Fluoxetine 32 mg kg ⁻¹ per day in water on PNDs 35–60 | PNDs 15, 21, 35 and 60 | Forebrain neocortex HDAC mRNA exp Histone acetylation EPM—PND 60 FST—PND 60 | Decreased MS-induced ↓ time in open arms Elevated MS-induced ↑ immobility in FST Reversed MS-induced ↑ H4K12 acetylation on PND 60 Fluoxetine Elevated MS-induced ↑ acetylation of H3K9, H4K8 & H4K12 on PND 60 | Theophylline worsened MS-induced anxiety and depression-like behaviours while modulating MS-induced ↑ histone H4K12 acetylation in adolescent Balb/c mice. Fluoxetine enhanced MS-induced ↑ expression of H3K9, H4K8, H4K12 in Balb/c mice on PND 60 |
| 12 | Determine the ability of zebularine to modulate early stress-induced changes in BDNF expression and methylation levels | Long-Evans hooded rats Abusive mother vs cross-fostering to caring mother for 30 min from PNDs 1 to 7 | Zebularine ICV 1200 ng per day on PNDs 83–89 | PND 90 | PFC BDNF mRNA methylation BDNF mRNA and protein exp | Reversed stress-induced ↑ BDNF methylation Attenuated stress-induced ↓ BDNF mRNA exp | Zebularine modulated early stress-induced changes in BDNF methylation and mRNA expression in Long-Evans hooded rats on PNDs 90 |
| 138 | Determine the ability of methionine and TSA to modulate epigenetic changes resulting from variations in maternal care | Long-Evans hooded rats High vs Low LG ABN | Methionine 2 μl (100 μg ml ⁻¹) ICV on PNDs 97–103 TSA 2 μl (100 ng ml ⁻¹) ICV on PNDs 90–97 | PND 97 | Hippocampus Exon 1, GR promoter methylation Histone 3-K9 acetylation 5' CpG of NGFI-A binding to exon 1, GR promoter GR mRNA and protein exp in hippocampus | ↑ methylation of NGFI-A in High LG ABN offspring to level of Low LG ABN offspring ↓ histone H3K9 association w exon 1, GR promoter in High LG ABN offspring to level of Low LG ABN offspring ↓ GR mRNA and protein exp in High LG ABN offspring to level of Low LG ABN offspring TSA ↑ GR mRNA exp in Low LG ABN offspring to level of High LG ABN offspring | Methionine and TSA modulate maternal care-induced changes in methylation of the exon 1, GR promoter in Long-Evans hooded rats on PND 97 |
| 62 | Determine the ability of methionine and TSA to modulate NGFI-A methylation and GR expression | M Sprague Dawley rats High vs Low LG ABN | Methionine 2 μl (100 μg ml ⁻¹) ICV on PNDs 97–103 | PNDs 90 and 100 | Hippocampus NGFI-A consensus sequence methylation | ↑ methylation of 5' CpG NGFI-A in High LG ABN offspring to level of Low LG ABN offspring | Methionine reversed hypomethylation of exon 1, GR promoter in adult High LG ABN offspring and ↓ binding of NGFI-A to |

Table 4. (Continued)

| Reference | Objective | Early stress | Intervention | Assessment age | Outcome measures | Results | Interpretation |
|-----------|--|--|---|----------------|------------------------|--|--|
| 61 | Determine the ability of methionine and TSA to modulate behavioural changes resulting from variations in maternal care | Long-Evans hooded rats High vs Low LG ABN | TSA 2 µl (100 mg ml ⁻¹) ICV on PND 90–97 Methionine 2 µl (100 µg ml ⁻¹) ICV on PND 97 TSA 2 µl (100 mg ml ⁻¹) ICV on PND 97 | PND 97 | CORT FST OFT | ABN offspring ↔ methylation of 3' CpG of NGFI-A ↔ global DNA methylation levels ↓ histone H3K9 association w exon 1, GR promoter in High LG ABN offspring to level of low LG ABN offspring ↓ GR protein exp in High LG ABN offspring to level of Low LG ABN offspring ↑ immobility in FST in High LG ABN offspring to level of Low LG ABN offspring TSA ↑ GR mRNA exp in Low LG ABN offspring to level of High LG ABN offspring High LG ABN offspring Methionine ↓ time in inner field in High LG ABN offspring to level of Low LG ABN offspring TSA Attenuated Low LG ABN induced ↓ time in inner field to level of High LG ABN offspring ↔ Maternal care, methionine or TSA on locomotor activity | GR promoter in M Sprague Dawley rats on PND 100. TSA ↑ GR mRNA expression in Low LG ABN offspring to level of High LG ABN in Sprague Dawley rats on PND 100 TSA attenuated anxiety behaviours in Low LG ABN offspring while methionine ↑ anxiety behaviours in High LG ABN Long-Evans hooded rats on PND 97 |

Abbreviations: ↑, increased; ↔, no change; ↓, decreased; 5-AZA, 5-aza-2'-deoxycytidine; BDNF, brain-derived neurotrophic factor; CORT, corticosterone; EPM, elevated plus maze; Exp, expression; F, female; FST, forced swim test; GR, glucocorticoid receptor; HDA, histone deacetylase; ICV, intracerebroventricular; LG ABN, licking grooming arch back nursing; M, male; mRNA, messenger ribonucleic acid; MS, maternal separation; NGFI-A, nerve growth factor-inducible protein A; OFT, open field test; PFC, prefrontal cortex; PND, post-natal day; PO, peroral; TSA, trichostatin A. Acute desipramine administration: 10 mg kg⁻¹ IP at 24 h and 5 h prior to behavioural testing; 20 mg kg⁻¹ IP 1 h prior to behavioural testing. Chronic desipramine administration: 20 mg kg⁻¹ per day IP for 14 days before behavioural testing; last dose 30 min before behavioural testing. ^aEarly 5-AZA: 5 mg kg⁻¹ (alternate days) from PND 2 to 9 OR 10 mg kg⁻¹ on PND 5 and 9. Late 5-AZA: 5 mg kg⁻¹ per day from PND 28–36. Early VPA: 3 mg kg⁻¹ from PND 2 to 9 OR 100 mg from PND 2 to 4 + 200 mg from PND 5 to 7 + 300 mg from PND 8–9 or 100 mg from PND 2–5 + 200 mg PND 6–9. Late VPA: 200 mg kg⁻¹ per day from PND 28 to 36.

modulate changes in histone modifications may be time-dependent. It is hypothesised that such time-dependent effects of valproic acid occur as decreased frontal cortical H3K9 monomethylation (due to maternal separation) is the cause of reduced acoustic startle responses, because it results in decreased expression of key genes involved in fear conditioning. As such, administration of valproic acid early in life reverses decreases in H3K9 monomethylation that occur due to separation, thereby preventing reduced expression of those genes involved in fear conditioning, thereby increasing acoustic startle responses compared with separated rats treated with vehicle.

Taken together, results from studies examining the modulatory influence of epigenetic-modifying drugs illustrate that changes in both DNA methylation and histone acetylation of candidate genes that occur in response to early environmental adversities are amenable to intervention. Of particular interest, administration of drugs in adulthood still appears to result in modulation of changes in the epigenome induced by early life stress. As such, earlier intervention with epigenetic-modifying drugs may be able to prevent the negative influence early stress exerts on the epigenome and protein expression of key candidate genes, including those involved in stress system regulation, and the influence such epigenetic changes exert on behaviour and disease susceptibility (Table 4).

DISCUSSION

It is widely accepted that individuals exposed to adversity in childhood tend to be relatively resistant to pharmacotherapy in clinical practice.^{142–144} Current interventions that aim to reduce the negative influence early stress exerts on later disease susceptibility are minimal at best. Findings from this review, although from animal studies only, suggest that some targeted interventions, particularly during early life, have the ability to attenuate or even reverse changes in neurobiology and behaviour that occur after adversity in childhood.

Findings from animal studies indicate that behavioural interventions such as SMG and MH, exercise and pharmacotherapies such as epigenetic-modifying drugs are likely to be most efficacious in reducing the negative consequences of childhood adversity. Each of these interventions modulates specific early stress-induced changes in neurobiology on both cellular and behavioural levels. Modulation of the latter is likely to be of most importance from a clinical and translational perspective.

The relevance of interventions such as SMG and MH, which potentially act through enhancing oxytocin signalling within the brain, is supported by reports of altered oxytocin levels following early stress. Exposure to adversity of early stress has been shown to alter OXTR expression and immunoreactivity in animal models of early stress,^{33,145,146} and also in children¹⁴⁷ and adult humans.^{148,149} From a translational standpoint, this is of interest, as while it may be possible to implement behavioural interventions in children exposed to early adversity, behavioural therapies are less likely to be as well tolerated in adolescents and adults. As such, oxytocin administration may represent a novel way to enhance oxytocin signalling in these individuals, thereby attenuating the influence childhood stress exerts on neurobiology across the lifespan, and the predisposition to later disease. Additional research is required in animal models to ascertain the mechanisms underlying the influence of SMG and MH, and to quantify their effects on the oxytocin system. It may then be possible to begin trialling these behavioural therapies in humans, to ascertain whether administration in childhood can reverse the sequelae of early stress, preventing the development of psychiatric disorders, and if intervention later in life can influence the extent of treatment resistance commonly seen in those with a history of childhood adversity and established psychiatric conditions.

From a translational perspective, the minimal side effect profile of exercise makes it a promising therapeutic option for both the prevention and treatment of psychiatric conditions. It can be adjusted on a patient-by-patient basis according to comorbidities and functional status.^{150–152} Clinical models point towards improved relapse prevention in patients treated with exercise compared with those treated with some pharmacotherapies,¹⁵³ and synergism between some drug therapies and exercise exists.¹⁵⁴ Findings from animal models also indicate that exercise can attenuate some of the negative neurobiological changes that result from early adversity. Exercise may be of benefit in the clinical setting, potentially acting as a preventative measure reducing the sequelae of childhood adversity and decreasing the predisposition to psychiatric disease. In those with current psychiatric conditions and a history of childhood adversity, the antidepressant- and neuroplasticity-enhancing effects of exercise may enable it to attenuate the extent to which early adversity influences neurobiology, thereby potentially reducing treatment resistance. Further work is required to delineate how to translate exercise therapy into human studies and then clinical practice. The influence the type, duration and frequency of exercise exerts on its modulatory ability requires investigation to ensure its benefits are obtained. The age at which exercise therapy should be introduced in order for it to act as a preventative measure following childhood adversity must also be established.

The ability of epigenetic-modifying drugs, such as DNA methylation inhibitors and histone deacetylase inhibitors, makes them a promising option to alter neurobiological changes induced by early stress across the lifespan. Additionally, their effects are more wide-ranging than those of other pharmacotherapies, in that they influence not only epigenetic changes induced by early stress but also the resultant alterations in neuroendocrine axis regulation and behaviour. Additionally, they appear to be able to effectively modulate early stress-induced changes in adulthood, often to a greater degree than other pharmacotherapies such as antidepressants, which can be less effective later in life. Given the positive findings from animal models of early stress, clinical studies are required to ascertain the efficacy and safety of epigenetic-modifying drugs in humans. It may be that if administered in childhood, DNA methylation inhibitors are able to reverse the hypersensitive, exaggerated stress response that frequently persists following childhood adversity, and the way in which it enhances the predisposition to psychiatric disorders development. As animal studies suggest that epigenetic changes can be modified in adulthood, intervention with these drugs later in life may act to attenuate the extent to which childhood stress influences neurobiology and the predisposition to disease.

CONCLUSION

Findings from this review suggest that the neurobiological sequelae of early stress can be attenuated or even reversed in animal models. Considerable effort is required before both behavioural and pharmacological therapies aimed at reducing the vulnerability to psychiatric disorders in those exposed to stress in childhood can be implemented in clinical practice. However, there are substantial gains to be had should the neurobiological sequelae of early adversity be amenable to intervention in humans. It may be possible to reduce or even eliminate characteristics of the vulnerable phenotype, thereby decreasing the incidence of psychiatric disorders in individuals with a history of childhood adversity.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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DISCLAIMER

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