



Injury, illness, and emotion: A review of the motivational continuum from trauma through recovery from an ecological perspective

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1. Introduction

Colloquial use of the term trauma brings together physical and mental distress, commonly occurring together in maladaptive responses following threat and injury. “Trauma” is also recognised following physical illness other than injury – an integrated neuroimmune system responds to traumatic tissue damage, metabolic dysfunction, and microbe-induced inflammation through the same interoceptive surveillance using signalling molecules and receptors shared between its neural and immune components (Blalock and Smith 2007). However, much of healthcare training still follows the traditional Western cultural “mind-body dualism” paradigm that physical symptoms (pain and other somatic distress) have a physical cause in tissue damage, inflammation, or metabolic disturbance (dyshomeostasis) - if that is not found during examination and investigation, symptoms must be “in the mind”, but for most patients/clients the “mental” label is alienating and stigmatising (Kirmayer and Gomez-Carrillo 2019).

In 2020 the International Association for the Study of Pain acknowledged that pain experience may be independent of nociceptive drive (Raja et al. 2020), persisting after healing or arising in its absence (chronic primary pain (Treede et al. 2015)). The term nociplastic identifies its source in altered neural plasticity centrally within the nervous system (Fitzcharles et al., 2021). Overall, genetic contribution to most nociplastic pain is modest, with genes responding to threat and reward and active in neurogenesis potentially introducing shared vulnerability to physical (pain) and mental (mood disturbance) trauma responses (Johnston et al., 2019; Ward et al., 2020). While acknowledging

evidence for genetic susceptibility in some, this review focuses on psychosocial vulnerability.

Nociplastic pain may develop as a form of somatisation, which has been defined as ‘a tendency to experience and communicate somatic distress and symptoms unaccounted for by pathological findings, to attribute them to physical illness, and to seek medical help for them’ (Lipowski 1988). Although trauma responses and somatisation are not generally considered together, complex trauma responses commonly include multiple somatic symptoms (Astill Wright et al., 2021). This review will show how pain and non-pain somatisation arising from trauma, metabolic disturbance, infection, or non-infective inflammation may persist maladaptively in a fearful environment through nociplastic mechanisms (Perez et al. 2015; Van Diest 2019; Meulders 2020). In this way, symptoms persisting after physical healing on the one hand, and anxiety, shame, grief, and depression persisting after emotional threat on the other, may represent a maladaptive neuroimmune spectrum (Eisenberger and Naomi, 2012; Ferris et al., 2019) motivating behaviour in support of a fearful agenda.

1.1. Trauma-recovery as a motivational continuum - the ecological perspective

Ecology describes the relationships of organisms in a particular environment to each other (social ecology) and to that environment (physical ecology). During ecological engagement, physical (physiological/movement-based) responses integrate with mental (feeling/emotional) responses in guiding and motivating behaviour. This review

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sees trauma-through-recovery as an adaptive arc of motivated ecological disengagement/re-engagement (Fig. 1). Negative interoceptive feelings and emotions arising homeostatically from threat and tissue injury/dyshomeostasis (malaise, pain, anxiety, fatigue) drive disengagement to facilitate self-protection and healing (Damasio and Carvalho 2013); positive interoceptive and proprioceptive emotion (wellbeing, vitality, joy, with hypothetical components developed below) energise re-engagement as active recovery follows healing (Farb et al., 2015; Fuchs and Koch 2014).

The lifetime narrative of ecological engagement determines vulnerability and resilience in highly complex ways. Threat/injury generate avoidant behaviour but also sensitise neuroinflammatory/neuroendocrine responses (allostatic load) (Danese and McEwen 2012; Berens et al., 2017); reward responses will be influenced in complex ways by adversity and wellbeing contributing to resilience, risk-taking, and hope (Ellis and Del Giudice 2014). An ecological approach to therapy facilitates progression along the continuum based on this motivational tapestry (Rossetini et al., 2018; Gallagher 2018). While acknowledging that pharmacological therapy has an important motivational role in recovery from trauma (for example, see (Forman-Hoffman et al. 2018)), the focus of this review is behavioural, and drug therapy is not discussed.

2. Context and objectives

This review is the second output from a larger project ‘Shared neuroimmune foundations of clinical pain and mood disturbance’ exploring common foundations for nociplastic pain and non-pain somatisation on the one hand, and mood and motivational disturbance including depression, anxiety, PTSD, shame, and grief on the other. The review seeks to integrate and present accumulating science largely published in the last 10 years in an accessible narrative form. Because of the wide range of fields of study and data sources, the research strategy has been exploratory - the review is thereby limited by a lack of exhaustive and systematic analysis of many areas discussed, but selection from and review of the accumulating archive has been rigorously cross-checked throughout. It is hoped that others working in those areas will offer constructive criticism, and that it may prompt further research to refute or support its conclusions.

The review acknowledges a broad definition of trauma, including

threat whether it is signalled interoceptively or exteroceptively; injury and/or illness predicted by threat; both physical and mental healing; persisting maladaptive self-reinforcing distress in some; and the processes and motivations operating through all aspects of recovery. Its ecological perspective interprets symptoms in terms of engagement with the physical and social environment - experiences and responses are framed in terms of behavioural inhibition (through the distress of fear, anxiety, pain or shame); facilitation of recuperation (through symptoms such as fatigue, anhedonia, or grief); and motivation of active re-engagement through wellbeing and hope.

One important theme emerging from this research is how social affiliation offers resilience to maladaptive trauma responses and social alienation introduces vulnerability, a topic returned to in section 6. Social alienation features in the epidemiology of chronic pain and somatisation, which share many features with persistent maladaptive mental distress including history of emotional adversity, adverse socioeconomic status, and cultural factors, potentially modulating injury and illness responses into neuroimmune persistence (Maercker and Horn 2013; Chiao and Mathur, 2016; Mills et al., 2019; Beutel et al., 2019).

2.1. Key objectives

- 2.1.1 To make explicit the integrated nature of evolved psychoneuro-immune (mind-body) biology, helping to reframe the culturally accepted dualistic paradigm to facilitate grasp of complex clinical body-mind influences.
- 2.1.2 To explore how integrated mind-body surveillance of all salient experience feeds into the individual’s unique developmental self-narrative viewed as an archive of successful and unsuccessful ecological engagement. The embedding of a dynamic self-image within this allostatic archive is discussed.
- 2.1.3 To illustrate how neuroimmune learning within this archive guides adaptive development by sensitising somatic (neuroendocrine/neuroinflammatory) and emotional responses, together anticipating and preparing for future engagement, but in so doing generating allostatic load and introducing vulnerability to maladaptive responses.

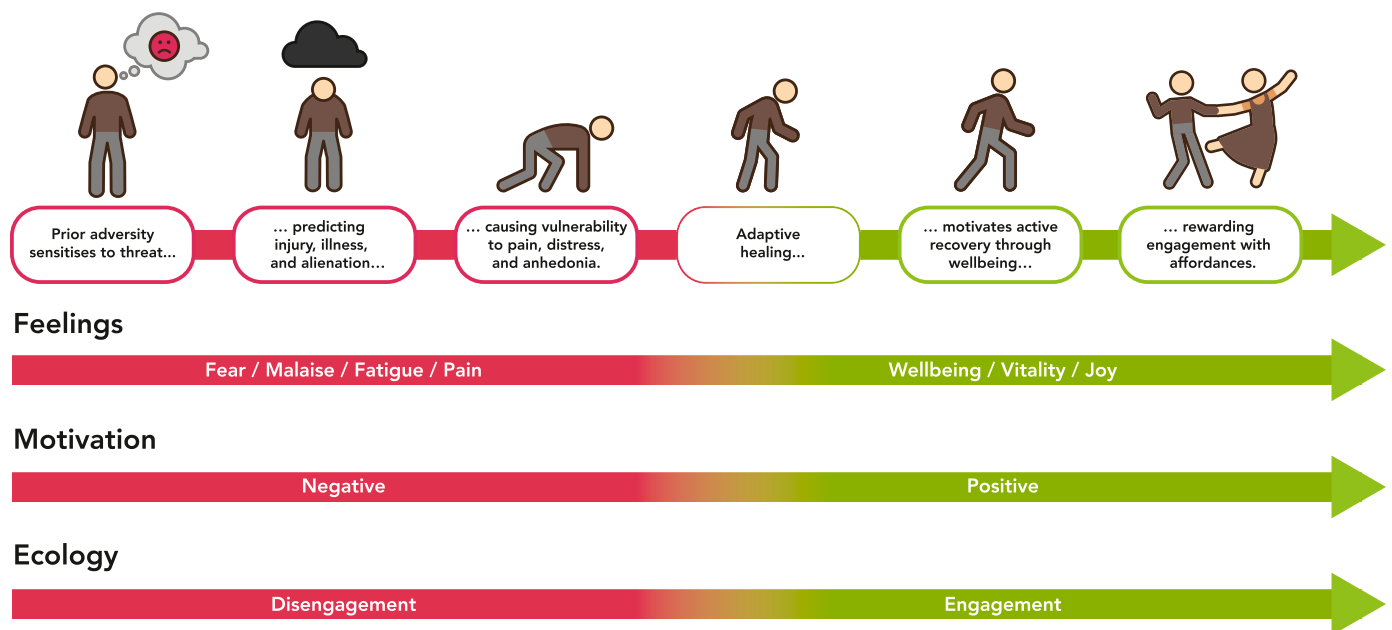


Fig. 1. The motivational continuum of traumatic disengagement/re-engagement. The neuroimmune system’s complex but seamless operation predicts and anticipates injury and illness from homeostatic surveillance, prompts self-protection and self-care, guides healing, and rewards active recovery.

- 2.1.4 To show how trauma exemplifies salient ecological engagement and trauma ‘memory’ within the neuroimmune learning archive epitomises allostatic vulnerability.
- 2.1.5 To explore how ‘mental’ and ‘physical’ sensory processing share central neural networks sensitised by the allostatic archive and how maladaptive emotional and somatic distress are founded in this shared archive of allostatic vulnerability.
- 2.1.6 To weave a motivational tapestry resulting from both archived and current ecological engagement and draw together themes relevant to supportive therapy across this distress spectrum, suggesting areas for future research.

3. A selective neurobiology of complex trauma

Consider this scenario as a backdrop to discussion. Martha, aged 35, is injured in a motor collision in which her husband is killed. She has two children under 10, gave up employment when she married, acquiesced in her husband taking important family decisions over the years, and has previously experienced anxious low mood at times of personal stress. Her injury is a stable compression fracture of a single lumbar vertebra, very painful on mobilisation from the time of injury but showing radiological healing at 6 weeks. Although typical recovery by this stage would include active mobilisation with modest reducing discomfort, she is developing fearful progressive lumbar pain which extends and amplifies to a widespread pain syndrome meeting diagnostic criteria for fibromyalgia (Sarzi-Puttini et al., 2020). She receives help from her mother and additional social support.

A biopsychosocial perspective (Borrell-Carrio et al., 2004) views this injury within complex mutually influential systems. Both arms of Martha’s neuroimmune system register and monitor tissue damage; sensory interpretation is biased by memory from her trauma; an older implicit archive from her experiences as daughter, student, employee, wife, and mother offers limited personal agency as single parent; the willing support offered by her mother coupled with pitying sympathy from her community encourages her to tolerate and even value the damaged self-image which this attention builds onto previous experience, and she passively accepts her developing disability.

Martha’s story highlights complexity in aetiology, but also in diagnostic categorisation across the mind-body distress spectrum, as she meets criteria for PTSD and major depressive disorder as well as fibromyalgia. There are parallels between presentations of fear-conditioned physical states (many cases of nociplastic pain and somatisation) and fear-conditioned emotional states (anxiety and PTSD) supporting shared aetiological pathways. Martha’s syndrome had a sudden and highly arousing onset like many cases of PTSD, but some persisting pain syndromes such as fibromyalgia secondary to inflammatory arthritis (Lee et al., 2013) arise gradually through conditioning to recurrent painful threat, like most cases of generalised anxiety disorder to social threat. Other cases of anxiety and nociplastic pain develop with little or no recognisable trigger, raising the possibility of sensitisation to non-noxious triggers following earlier adversity (McLaughlin et al., 2010; You et al., 2019). By adopting a unified perspective that past experience of threat and injury may bias all facets of current ecological interaction, this framework emphasises vulnerability alongside the trauma itself (Gradus and Galea 2022).

3.1. “Slow pain” exemplifies mind-body integration in trauma memory

Adaptive acute pain and maladaptive chronic (nociplastic) pain are two very different things (Fitzcharles et al., 2021). Forceful mechanical trauma from the physical impact of Martha’s injury generates immediate but temporary pain through high-threshold mechanoreceptor activation

(“fast” pain, which from an ecological perspective can be considered exteroceptive, prompting rapid avoidance behaviour). Subsequent tissue responses to her vertebral fracture initiate “slow” pain through a combination of mutually influential neural and immune processes (Maruyama 2021). Similar fast and slow elements operate across many behavioural domains - Daniel Kahneman describes the experiencing self (fast), and the remembering self (slow) in his book ‘Thinking, fast and slow’ (Kahneman 2011), emphasising that the remembering self dynamically monitors the ongoing impact of experience as it guides decision-making.

Maladaptive pain co-occurs with the spectrum of fear/anxiety syndromes, particularly post-traumatic stress disorder (PTSD), as threat memory dominates cognition and behaviour (Asmundson and Katz 2009). It also co-occurs with depression, and accumulating evidence places anhedonia (a key feature of depression) within the neuroimmune repertoire following tissue injury (Borsook et al., 2016; Lee et al., 2018; Harvey 2021). This review explores common ground shared by distressing somatisation (including chronic pain) and maladaptive emotional distress such as persisting anxiety and depression, disabling shame, and complicated grief, proposing that the mechanisms whereby adaptive responses become maladaptive depend on shared central neural networks operating across this spectrum.

The neural-with-immune “slow” nociceptive response is imprinted (“remembered”) as a platform for adaptive healing and recovery (Rahn et al., 2013; Harte et al., 2018; McCarberg and Peppin 2019). This plasticity may be reflected in structural brain changes observed in maladaptive physical and emotional distress, and there remains little doubt such changes are responsible for symptoms and/or reflect the allostatic vulnerability which underlies them (Whittle et al., 2014; Mansour et al., 2014; McCrory et al., 2017; Opel et al., 2019). Prospective comparisons of maladaptive progression following physical vs. mental trauma are limited (Elman and Borsook 2018), but evidence suggests that systems handling interoceptive flow, threat, salience and attention, reward, and neural learning are active irrespective of whether somatic or emotional processing triggers the persisting distress (Brown and Morey 2012; Dymond et al., 2015; Perez et al., 2015; McCarberg and Peppin 2019; O’Connor 2019; Schmaal et al., 2020).

3.2. Functions of trauma memory

Tenderness and stiffness inhibit activity, but highly complex central injury-related plasticity permeates networks generating salience, attention, and emotion, and planning motor activity, as well as those guiding tissue repair. In adaptive recovery this multifaceted dynamic imprint is overwritten during ecological engagement; in maladaptive persistence it self-reinforces with increasing disengagement. The neural influence of any injury imprint distributes into three domains - sensory-discriminative (defining location and nature), affective-motivational, and cognitive-behavioural (Melzack and Casey, 1968). Hypothetically all interoceptive sensory flow elaborates affective-motivational and cognitive-behavioural influence. The affective-motivational domain modulates behaviour through distress, and the cognitive-behavioural domain supports strategic recovery management, developed further below. Pain is a specialised interoceptive modality, integrated with surveillance reporting tissue status through the insular cortex – salient nociceptive foreground against homeostatic interoceptive background (Craig 2002; Critchley and Harrison 2013). As dyshomeostasis normalises through adaptive healing, interpretation shifts from nociception to healthier interoception, adjusting motivational valence as ancient self-reinforcing recovery repertoires are recruited.

The less intuitive cognitive-behavioural domain’s role can be viewed as strategic oversight of ecological engagement, integrating current

events into the self-narrative while anticipating imagined futures (Markus and Nurius 1986; Delafield-Butt and Trevarthen 2015). This review proposes that the ongoing neuroimmune self-narrative is both the data source and operating environment for cognitive-behavioural strategic oversight (discussed in section 5.3). Trauma fundamentally damages self-image, the neural foundations of which can be considered to lie within the allostatic archive of data derived from the body (Damasio 2003). During recovery, cognitive-behavioural oversight must assess the implications of dyshomeostasis (illness, injury) and ecological disengagement (physical and social disability), and judge how they fit with the imagined future held in mind. As neuroimmune surveillance updates perception of the structure and function of the affected body during recovery, self-image is updated through complex evolving plasticity (Conway 2005). Self-efficacy is perceived when self-image again becomes a sufficiently good strategic fit with the imagined future (Benight and Bandura 2004).

In behaviour choice, conditioning and priming (activated subcortically) may direct attention to predicted adversity, but the prefrontal cortex (PFC) has strategic oversight, modulating perception, facilitating or inhibiting new implicit associations, and influencing resulting motivational states (Hofmann 2008; Craske et al., 2018) illustrated in Fig. 2.

Autobiographical (explicit) memory built into primate neural repertoires during recent evolution co-activates and interacts with ancient (implicit) mechanisms of associative learning, following the same strategic agenda for survival and flourishing (Reder et al., 2009; Dew and Cabeza 2011; Dolan and Dayan 2013). This introduces potential for perverse mutually reinforcing feedback within the complex systems at work in human trauma responses through the following interacting mechanisms. Firstly, vulnerability (whether conceptualised as trauma memory or allostatic load) may generate contextual emotional arousal,

enhancing and biasing perception and interpretation of ongoing sensory experience and new memory formation (McIntyre et al., 2012; Phelps et al., 2014). Secondly, when memory recall deliberately or reflexively imagines a scenario, the memory trace is destabilised ((Lane et al., 2015; Bermúdez-Rattoni and McGaugh 2017) and see (FERNYHOUGH 2013) chapter 6. ‘Negotiating the Past’). Thirdly, by repeatedly recalling traumatic memories with their arousing emotional connotations (ruminating), not only may Martha’s trauma imprint be reinforced, but an increasing number of contexts – physical environments, social encounters, self-generated thoughts – may be conditioned to her pain (Van Diest and Ilse, 2019; Meulders 2020).

There is another dimension to the concept of memory as self-narrative which makes this discussion more complex. Rather than acting simply as a storage process, the constructivist model of memory (Axmacher et al., 2010) recognises the instability of recalled memory as a mechanism whereby the self-concept is susceptible to change (positive or negative). When reconsolidation reframes autobiographical memory under adverse ambient emotional influence, not only may adverse implicit responses be reinforced but the archived self-narrative itself may be negatively re-written. However, memory destabilisation also introduces therapeutic opportunity by positively influencing the emotive connotations of trauma memories and modulating the aversive quality of their conditioned associations (Monfils and Holmes 2018; Kindt 2018; Milton 2019).

4. The evolutionary foundations of trauma vulnerability

4.1. A seamless integrated neuroimmune system

From early in multicellular life, immune and neural functions have co-evolved in recognising risk (of intoxication, predation, or

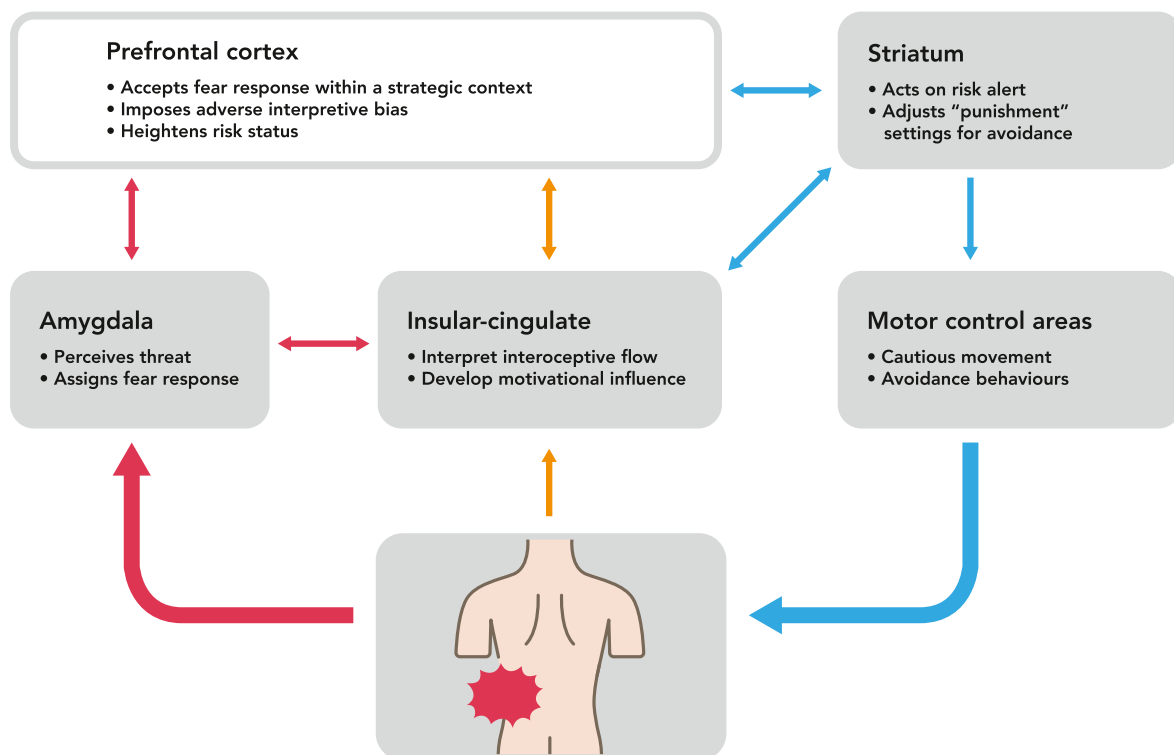


Fig. 2. Prefrontal cortex strategically oversees behavioural response to threat and injury. In this illustration, the PFC accepts the amygdala’s fear response, adversely biases insular-cingulate interpretation of body signalling (Medford and Critchley 2010) so no interoceptive threat is overlooked, and raises risk awareness through cortico-striatal reward settings to “cautious avoidance”. The potential for maladaptive reinforcement within these systems is evident – the critical target for therapeutic input is the belief-fear relationship at prefrontal cortex-amygdala where extinction of fear-related conditioning occurs.

parasitisation) and opportunity (of nutrition or symbiosis) (Blalock and Smith 2007; McFall-Ngai et al., 2013). Through cross-domain (physical-mental) integration, tissue-based neuroimmune responses influence mood and behaviour: immune-generated sickness behaviours modulate physical and social engagement following injury, infection, and other tissue-damaging illness including malignancy (D'Mello and Swain 2017); immune activation may directly bias social engagement, sensitising the amygdala to interpersonal threat (Cowan et al., 2018; Eisenberger and Moieni 2020); and anhedonia induced by physical as well as mental injury facilitates rest by reducing the invitation to ecological engagement (Borsook et al., 2016; Harvey 2021). The primeval roots of mental distress presenting as anxiety and depression are increasingly recognised in repertoires of defence against and recovery from physical injury, illness, and infection ((LeDoux 2015) chapter 3 'Life is dangerous') (Raison and Miller 2017; Khalsa et al., 2018; Harvey 2021)).

4.2. Homeostasis and allostasis

Homeostasis implies a data-gathering process resulting in retrospective adjustments to physiology or behaviour. Its contemporary iteration, allostasis, recognises a prospective mechanism in which the cumulative archive of learning identifies trends and predicts and anticipates risk and opportunity (Danese and McEwen 2012; Schulkin and Sterling 2019). The allostatic archive from childhood and adolescence powerfully influences adult health and behaviour (Shonkoff and Garner, 2012); even preconception influence may be transmitted epigenetically to the child (Bohacek et al., 2013).

Ancient surveillance systems providing the foundations for physiological homeostasis have developed through mammalian-to-human evolution to monitor and guide social interaction for individuals and groups (Beauchaine et al., 2011; Saxbe et al., 2020). Archived learning from social adversity sensitises to neuroendocrine, immune-inflammatory, and emotional arousal (Slavich and Irwin 2014; Berens et al., 2017; Frank et al., 2019), thereby guiding individual development (Ellis and Del Giudice 2014). Vulnerability to arousal during subsequent exposure to triggering contexts (allostatic load) predicts health impacts including mental illness such as depression (Miller and Cole 2012; Naicker et al., 2021); nociplastic pain (Cay et al., 2022); a spectrum of non-communicable diseases (Kivimäki et al., 2020); and early death in some (Rod et al., 2020). Social and emotional support during adversity in childhood and adolescence may mitigate both the formation of the allostatic archive and its unhealthy expression (Bellis et al., 2018; Ungar and Theron 2019; Masten et al., 2021).

4.3. Allostasis and memory

This review has used the term "imprint" following trauma to describe dynamic neural-with-immune plasticity which guides adaptive recovery, but which may be retained, leading to maladaptive outcomes. Modelling suggests that the nociceptive imprint of central sensitisation is integrated with other neural memory processes (Rahn et al., 2013; McCarberg and Peppin 2019), including priming and nocebo and placebo responses (Rossetini et al., 2018; Thomaidou et al., 2021), and potentially immune learning within the innate immune system ("trained immunity" (Netea et al., 2020)), and learning arising through Pavlovian conditioning (Hadamitzky et al., 2020).

Martha's case illustrates the imprint's complex short- and medium-term functions - unloading the injured area, stridently arguing for rest during early recovery, promoting tissue healing, re-shaping injured self-image, prompting reflective imagination about possible futures, and rebuilding motivation during healing and re-engagement, among many others. But what is the relationship between this dynamic trauma memory and allostasis? This review proposes that this imprint, like all ongoing salient experience, feeds into and reshapes the individual's allostatic archive. It argues further that this neuroimmune archive

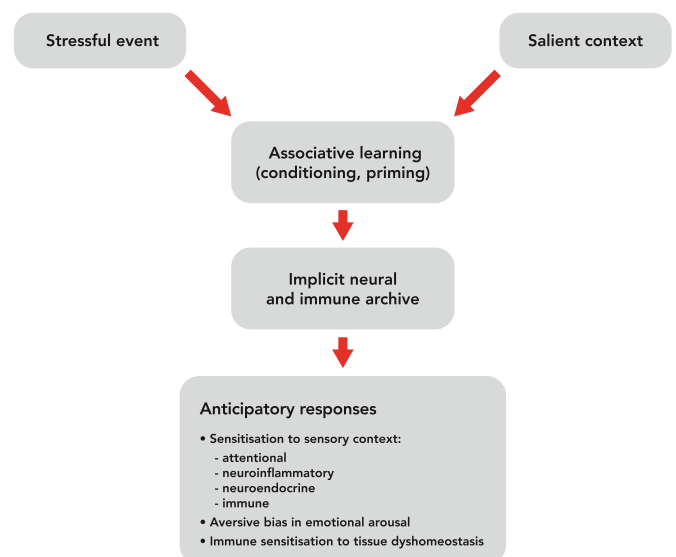


Fig. 3. Implicit memory and allostatic load. Nociplastic pain and non-pain somatisation may be viewed with maladaptive mood disorders as an integrated spectrum of somatic and emotional distress predicted by allostatic load and mitigated by allostatic resilience, explored further below.

provides the data source for the unique individual self-narrative as it continually registers traumatic and non-traumatic ecological engagement, builds self-knowledge, refines self-image (Conway 2005), acquires skills (Araujo and Davids 2011), and establishes a unique and complex balance of resilience and vulnerability (McCrorry et al., 2017; Masten et al., 2021). Although published research on allostatic load may not detail the mode in which it is archived, this review considers it a composite of relevant neural and immune memory, operating largely unconsciously (Beauchaine et al., 2011). It views the influence of the allostatic archive in aggregate (Fig. 3), including sensitised neural sensory responses (Harte et al., 2018); neuroendocrine and neuro-inflammatory responses (Berens et al., 2017); and biased emotional responses (enhancing fear and reducing reward (Phelps et al., 2014; Wiech et al., 2014; Borsook et al., 2016)). These influences are established through altered neurochemical balance and neural network connectivity (Harte et al., 2018); immune sensitisation to tissue dyshomeostasis (Rankin and Artis 2018); and neural-immune modulatory crosstalk (Yirmiya and Goshen 2011; Jakob et al., 2020), all of which may be epigenetically archived (Hunter and McEwen 2013).

4.4. Allostasis and the predictive brain

The term surveillance has been used above to describe the homeostatic process of data collection because of its familiarity, but it does not precisely reflect hypothesised Bayesian inference in allostatic operation. Although explicit (autobiographical) memory is intuitively considered retrospective, it supports predictive decision-making through imaginative virtual comparison of possible scenarios ((Schacter et al., 2012) and see (Passingham and Wise 2012) pages 296–8). The whole memory archive is predictive (Brown and Brune 2012; Clark 2013), anticipating threat and opportunity, influencing perception, interpretation, and ongoing learning, guiding decisions and actions by influencing attention and motivation moment-by-moment. The brain's data processing continually updates its "best-fit" predictions as experience accumulates, prompting optimal pre-emptive responses. Rather than the accepted "bottom-up" experience of interoceptive and exteroceptive sensory perception that we have been taught, Bayesian inference-based modelling proposes that the brain not only predicts what will happen next but

translates those predictions into conscious experience “top-down”. The models of reality that the brain constructs, and the experiences predicted to follow at any point in time, are continually under review as a key regulator of neural learning. Prediction errors (mismatches between predicted and actual experience (Krawczyk et al., 2017)) generate salient arousal which can be resolved by changing the prediction (perceptual inference leading to new learning), or changing behaviour to fit the prediction (active inference) (Seth and Friston 2016). “Real-life” surveillance provides Bayesian prediction with the salient experiences of ecological engagement from which the allostatic archive is built, and validates its ongoing operation through prediction error recognition, but moment-by-moment experience is, in Professor Seth’s term, hallucinated into consciousness based on the allostatic archive.

This complex recent perspective on neural function is emphasised because it appears central to the development of maladaptive trauma responses. It proposes that conscious experience, including its motivational influence, is constructed “on the run” as past developmental experience uniquely anticipates what will happen next. It argues that ‘all our perceptual modalities ... are things an organism does, not passive information feeds for a centralised “mind”’ ((Seth 2021) page 129), and that predictions based on the allostatic archive ‘do not merely bias our perception. They are what we perceive’ (ibid. page 115). In this work entitled ‘Being You: a new science of consciousness’, Professor Seth states ‘The “you” in question is the assemblage of self-related prior beliefs, values, goals, memories, and perceptual best guesses that collectively make up the experience of being you’ (ibid. page 220). Fearful health beliefs or hopeful imagined futures are thereby predicted into existence by this archive, within the emergent phenomenon of consciousness into which feelings and their motivations are integrated ((Damasio 2010) chapter 8, “Building a conscious mind”), (Seth and Friston 2016; Barrett 2017). From this perspective, nociplastic pain is experienced not because allostatic load biases sensory perception and interpretation, but because allostatic predictions, presented within an adverse psychosocial context, become conscious experience (Hechler et al., 2016).

5. Self - body and mind - in trauma-induced ecological disengagement

When painful injury results in low mood, or depression is associated with accentuated pain, the culturally accepted paradigm attributes altered mood to pain and *vice versa*. However, accumulating evidence argues that they co-occur and co-operate as outputs of a single system working to the strategic agenda of preserving the fully integrated physical-mental self.

5.1. Cross-modal and cross-domain modulation of sensory flow

Salient responses to threat/injury are not simply elicited by a visual or audible signal or tissue nociception in isolation but by a complex ecological context ((Gruber and McDonald 2012) and see (Passingham and Wise 2012) pages 220–264) in which different sensory modalities prime and sensitise each other, influencing perception qualitatively, not simply summatively (for examples, see (Kayser et al., 2010; Gori et al., 2011)). To what extent does signalling perceived interoceptively (physical) or exteroceptively (mental) within a salient context not only influence current perception across domains, but also sensitise and bias future responses as it is embedded in the allostatic archive? Neuro-immune surveillance of tissue status (physical) influences motivation (mental) (Critchley and Harrison 2013), and emotional arousal (mental) sensitises future neuroendocrine and neuroinflammatory responses

(physical) as allostatic load (Berens et al., 2017); recovery behaviour (physical) modulates the distress of pain (Basso and Suzuki 2017; Fuchs and Koch 2014) and resets anhedonia (mental) with evidence for long-term benefit (Hallgren et al., 2016) suggesting cross-domain influence becomes embedded; the accumulation of diverse adverse childhood experiences introduces vulnerability to both physical and mental symptoms in adulthood, rather than domain restricted adversity-distress pathways (McLaughlin et al., 2010; Ashton et al., 2016; You et al., 2019).

5.2. Self and self-image through trauma-to-recovery

Self is a multifaceted concept, and different disciplines develop and emphasise different perspectives. The ecological perspective of this work seeks to explore how an individual’s self-perception develops, adapts, and is archived within a unique neuroimmune narrative, as the physical body engages with its social and physical environment. Any major life event alters self-image - social threat or physical injury may risk stigmatisation and alienation by affecting behaviour and appearance, and inhibit social re-engagement through diminished perceived self-efficacy. Recent analysis of complex PTSD acknowledges the central importance of self in ecological engagement for trauma recovery by including disturbance in self-organisation associated with extremely negative self-concept and prominent behavioural avoidance in the diagnostic criteria for this particularly severe pattern of trauma response (Maercker et al., 2022). If therapeutic focus is limited to physical ability and emotional wellbeing without attention to self-image, motivation for recovery may be compromised.

This review proposes that self-image is founded in the allostatic archive of interoceptive/proprioceptive surveillance of ecological engagement, reflecting the health and physical and social competence of the physical body and providing the foundation for risky ecological engagement ((Conway 2005; Delafield-Butt and Trevarthen 2015; Peers et al., 2020) and see (Damasio 2010; Seth 2021)), while recognising the importance of peer feedback in shaping self-image within our empathic socially interdependent neurobiology ((Lieberman 2013) pages 189–92).

5.3. Self-organisation within an individual’s unique neuroimmune narrative

All post-trauma re-engagement depends on purposeful physical activity, the developmental origins of which can be traced back to foetal and neonatal neural learning, building continually through childhood and adolescence into adulthood (Delafield-Butt and Trevarthen 2015). These authors emphasise how all physical activity occurs within and contributes to an individual’s unique personal narrative (Fig. 4). Successful and skilful prior execution of similar activity will predict reward, and so “Each step carries the organism purposefully in time and space to a set of relations with new affordances, and new meaning” ((Delafield-Butt and Trevarthen 2015) and see also (Rietveld and Kiverstein 2014; Withagen et al., 2017)). But prior trauma may predict threat, limiting encounters with new affordances through self-reinforcing avoidance (Gallagher 2018).

All living organisms are self-organising systems. Self-organisation may be defined in systems terms as ‘the ability [for systems] to structure themselves, to create new structure, to learn, diversify, and complexify’ (Meadows 2008). Following trauma, the neuroimmune self-system seeks to make sense of events from its own unique data archive. The self-organised neural “structure” of trauma may be visualised in altered brain imaging (Whittle et al., 2014; Mansour et al.,

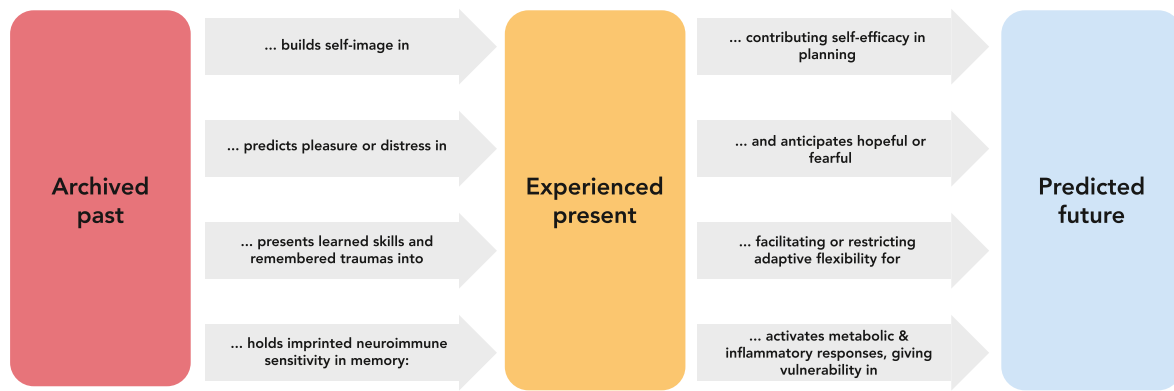


Fig. 4. Trauma and recovery within the neuroimmune self-narrative: individuality and continuity. All self-generated activity is guided by the individual's unique allostatic archive as it predicts the risks or benefits from its proprioceptive consequences. Competent and confident engagement arises within this continuing narrative which links from experience (the past) through behaviour (the present) to imagined possible selves (the future).

2014), and successful therapy can be shown to facilitate self-reorganisation back towards the pre-injury state (Quide et al., 2012; Thomaes et al., 2014; Ashar et al., 2022). In wider systems terms, although structural self-reorganisation occurs through internal information transfer, much of that information (and the structural change it produces) is generated through ecological engagement, providing motivation and guiding appropriate adaptive (but sometimes maladaptive) development. This is particularly relevant after trauma, as the essence of recovery is re-establishing ecological fit.

Rehabilitation practice over recent decades in both mental health and physical disability has positioned the individual patient/client centrally within the support team, seeking to empower objective-setting based on personal aspirations and social context (Sowers 2012; Jesus et al., 2022). This review's ecological perspective fundamentally supports this approach - promoting the patient/client within the support team places agency for ecological engagement with the only individual who has direct neuroimmune access to the systems which must adapt for recovery.

6. Alienation, fear, and the long-term impacts of trauma

Social alienation and socioeconomic poverty are significant contributors to syndromes of maladaptive distress - nociplastic pain, anxiety/depression, and somatisation are all prevalent in socioeconomically challenged communities, linked to social disharmony, poor educational achievement, and childhood adversity ((Kessler and Bromet 2013; Mills et al., 2019; Beutel et al., 2019) and see (Wilkinson and Kate, 2018)). Human dependence on social affiliation runs deep in our evolved past, building from collaboration in non-primate social mammals and strengthened through the critical survival need of our primate, early human, and settling hunter-gatherer ancestors to belong and feel valued and safe under threat of predation and conflict ((Dunbar 2014) pages 305–11). Such experiences would prioritise empathic awareness to facilitate social affiliation within the evolution of homeostatic surveillance ((Walker and McGlone 2013) and see (Zaki 2019) pages 5–6) but would predict trauma from its loss through social exclusion. As contemporary humans largely share their hunter-gatherer ancestors' genetically determined neurobiology, this review assumes that acutely sensitive social surveillance will predict similarly severe adverse responses from contemporary experience of social exclusion. Its ecological analysis argues that self-within-social-context is the reference point for

processing trauma responses, and that emotional threat to self has acquired its influence on contemporary health and wellbeing through such affiliation-based evolutionary mechanisms (Meredith et al., 2008; Slavich and Irwin 2014; Ferris et al., 2019).

This review proposes that Martha emerged into adulthood significantly alienated from her physical as well as social environment, common in contemporary communities (Bronfenbrenner 1974; Brussoni et al., 2015; Bloomfield et al., 2016), sensitised to ecological risk, inherently generating homeostatic dissonance and allostatic load. Social alienation contributes to mental illness and the broader epidemic of non-communicable diseases that threatens contemporary public health (Hertzman and Boyce 2010; Davies et al., 2021; Harvey 2021; Cao et al., 2022), largely mediated by threat-responsive neuroinflammatory and neuroendocrine activation (Berens et al., 2017). The effects of such alienation are not primarily triggered by major physical or mental trauma, but from the daily emotional distress of loss of affiliation/discrimination (Geronimus et al., 2006; Bailey et al., 2017; Mathur et al., 2021).

6.1. The role of fear and the fear-avoidance model

The spectrum of presentation of persisting somatic symptoms ranges from largely nociceptive (rheumatoid arthritis pain and fatigue; gastritis), through amplification unexplained by tissue-based mechanisms (often associated with psychosocial dyshomeostasis), to symptoms persisting after any trigger has healed (nociplastic pain; chronic fatigue; functional dyspepsia), and including somatic distress arising without nociceptive trigger. While acknowledging a limited genetic predisposition to symptom generation, this review recognises fear as a key driver for maladaptive persistence as archived social adversity generates vulnerability by predicting threat to self. The fear-avoidance model of pain behaviour argues that fear of the distress of pain (and by extrapolation of other somatic symptoms) may condition symptoms to contexts of daily life which are not inherently threatening (Meulders 2020). The neuroimmune imprint following physical injury and illness may thereby be retained and reinforced in the same way as the imprint of social/emotional threat in anxiety/PTSD. The development of fearful somatisation as outlined in Fig. 5 may illustrate this process through cross-domain sensitisation. Somatisation is a frequent healthcare presentation associated with and predicting mood disturbance (in a population-based analysis of 70,000 child and adolescent healthcare

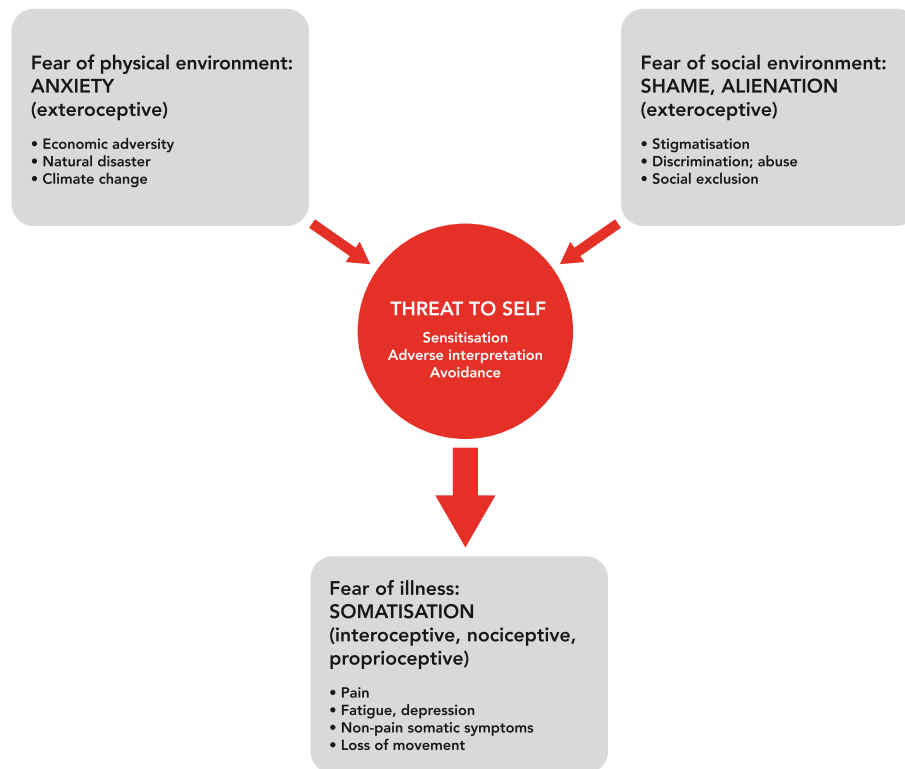


Fig. 5. Hypothetical cross-domain threat sensitisation from the self-perspective. Threat to self may be perceived in the physical or social environment, or through nutritional or metabolic dyshomeostasis. This illustration suggests how a threatening environment may sustain somatic symptoms through self-protective attention to and adverse interpretation of interoceptive flow.

records, the most reliable predictors of a first-recorded mental illness event were somatic complaints requiring healthcare intervention (Koning et al., 2019)).

Any interoceptive signal can potentially be rendered salient through fear (for example due to inaccurate health beliefs) and amplified and retained by attention and interpretation bias (Van den Bergh et al., 2002). Some symptoms of “long COVID” (Whitaker et al., 2022) within the current fearful pandemic may illustrate complex systems influence through reinforcing feedback between immune (anti-viral), neural-interoceptive (somatic dyshomeostasis), and neural-exteroceptive (community fear/isolation) signalling (Bartholomew and Baloh 2020; Horn et al., 2021) on a foundation of allostatic vulnerability (Wang et al., 2022).

7. Sourcing motivation through recovery: education, positive emotion, and behavioural commitment

The motivational continuum that this review highlights begins with fear and shifts during adaptive recovery to hope. The ecological perspective argues that it is only through behavioural expression of hope for a positive outcome resulting in committed exposure to and successful engagement with the feared contexts, that maladaptive belief can be overwritten (Cheavens et al. 2006; den Hollander et al., 2010; Judge et al., 2019). The hypothesis of cross-domain sensitisation argues that vulnerabilities resulting from mental experience will influence recovery from physical trauma and *vice versa*, for example through enhanced pain, anxiety, fatigue, and anhedonia. As a corollary, common barriers and opportunities may be encountered during recovery from mental and physical distress, determined as much by past experience as by present trauma. This section seeks to identify the sources of shared motivational influence on this journey, and to map them onto evidence-based therapies.

7.1. Vulnerability and resilience – onto what soil does the seed of trauma fall?

Archived neuroimmune learning has a fundamental role in recovery from trauma, introducing resilience or vulnerability (Daskalakis et al., 2013; McCrory et al., 2017; Masten et al., 2021). Fearful adversity leads to avoidance and behavioural inflexibility, the opposite of resilience. Hopeful recovery requires behavioural flexibility within an environment that offers choice (Carver et al., 2010; Gentili et al., 2019; Ungar and Theron 2019). It is acted out through exploratory ecological engagement (Alcaro and Panksepp 2011) rewarded by novelty (Guitart-Masip et al., 2010) and affordances (see below), facilitating exposure-based overwriting of the trauma imprint (extinction). However, when pain and fear constrain flexibility, the innate ecological relationships which motivate self-reinforcing recovery repertoires are undermined - the invitation to engage is reduced through anhedonia, and fearful avoidance limits opportunities for extinction behaviours.

7.2. Education's motivational role

In any human activity, ignorance introduces vulnerability by reducing choice, but education - sharing understanding - enhances resilience. In nociplastic pain and somatisation, maladaptive fear of a somatic cause is typically unfounded, and understanding the benign nature of the pain and other symptoms, such as through pain neuroscience education, is a key foundation for overwriting the maladaptive imprint (Joypaul et al., 2019). Negative communication, even the absence of reassurance, may generate nocebo effects inhibiting self-generated pain control and compromising active engagement (Rossettini et al., 2018).

7.3. Interoceptive emotion

“Interoception ... appears to be tightly linked to the self and survival through homeostatic maintenance of the body ... helping us to represent how things are going in the present with respect to the experienced past and the anticipated future” (Khalsa et al., 2018). The foundations of motivation are increasingly recognised in interoceptive/proprioceptive sensory flow (Critchley and Harrison 2013; Fuchs and Koch 2014) into which exteroceptive influence is integrated (Merker 2007). Through the established concept of interoceptive emotion (Craig 2002; Damasio and Carvalho 2013) homeostatic awareness of the health of the body interpreted within the insular cortex generates feelings of illness (introducing caution and distress) but also wellbeing, a positive motivational experience (Farb et al., 2015). Profound neuroimmune responses to extreme trauma may protect from distress by inducing dissociation, compromising access to interoceptive sensory flow (van der Kolk et al., 1995; Axmacher et al., 2010; Lumley et al., 2011; Payne et al., 2015) - following healing that same interoceptive flow can generate wellbeing, positively motivating adaptive recovery. Contemporary therapies for recovery from trauma including those based on mindfulness and movement emphasise interoceptive/proprioceptive awareness (Farb et al., 2015; Yu and McCracken 2016; Lumley and Schubiner 2019; Meehan and Carter 2020; Allen et al., 2021).

7.4. Proprioceptive emotion

‘[I]t is eminently plausible that reason has grown out of the sensory and motor systems and that it still uses those systems’ ((Lakoff and Johnson 1999) p 43); ‘[M]ovement is at the root of our sense of agency’

((Sheets-Johnstone, 2011) page xvii); ‘Actions are fundamental to learning’ ((Seth 2021) pages 113–5). The hypothesised concept of proprioceptive emotion (Fuchs and Koch 2014) proposes that the purposefully active animate body will motivate self-reinforcing recovery, resetting caution and distress while facilitating neural self-reorganisation. This review recognises proprioception’s influence through both neural and immune mechanisms. Physical activity enhances wellbeing and reduces pain through endorphin, cannabinoid, and other mechanisms (Basso and Suzuki 2017; Lesnak and Sluka 2020); prevents and corrects mood disorder (Hallgren et al., 2016; McDowell et al., 2019); potentiates neural plasticity (Pedersen 2019); and develops and enhances immune function (Duggal et al., 2019; Docherty et al., 2022).

This review’s ecological perspective predicts that physical activity will introduce neuroimmune benefit depending on the value ascribed to that activity within the individual’s unique neuroimmune narrative (Kirmayer et al., 2016). In general, engagement with natural surroundings and participation in group-based activities with affiliative cultural associations, ideally involving learning and practicing useful skills, will add value to exercise (Barton et al., 2016; Launay et al., 2016; Fancourt et al., 2021). Cognitive extinction of fear-conditioned inhibition through exposure therapy illustrates proprioceptive surveillance at work as maladaptive neural connectivity is restructured during successful *physically active* engagement with feared contexts (Hofmann 2008; Craske et al., 2018). Ecological re-engagement (Fig. 6) can thereby facilitate the overwriting of all maladaptive remnants of the trauma imprint - physical pain and fatigue, emotional distress and anhedonia.

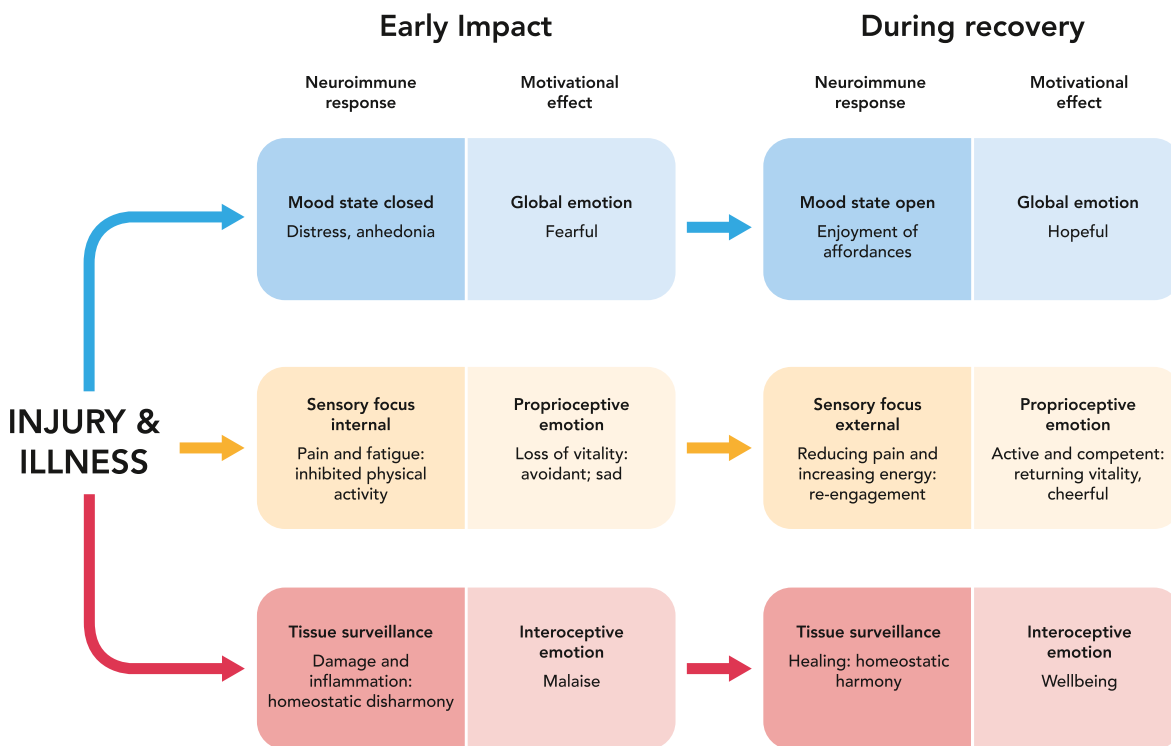


Fig. 6. Interoceptive, proprioceptive, and global emotion motivating recovery from injury or illness. Interoceptive/nociceptive (lower sequence) derives from the affected tissues; proprioceptive (middle sequence) arises from self-expression in purposeful activity; mood-related global emotion from reward settings in current operation (upper sequence) has complex sourcing including mental imagery.

7.5. Affordances

The concept of affordances ((Gibson 1979) chapter 8) was developed to focus attention on the process of engagement of an organism with its ecological niche through, for example, the sight of nutritious food or an opportunity for social interaction. Genetic priming underlies the concept but an organism exercises agency in responding to the ecological invitation (Withagen et al., 2017) - developmental experience may modulate the “coupling strength” of the interaction and influence any behaviour that emerges. This review emphasises a central role for affordances within ecological re-engagement during recovery from trauma (Rietveld and Kiverstein 2014; Krueger and Colombetti 2018; Gallagher 2018), motivating according to the affordance’s value within the individual’s developmental narrative. Cultural influence is important in building affordance value - “While evolutionary history reaches all the way up from brain circuitry to cultural forms of life, culture reaches all the way down to neuroplastic circuitry and epigenetic regulation; hence, human biology is fundamentally cultural biology and human environments are social environments, constituted by relationships with others and with cooperatively constructed institutions and practices” ((Kirmayer and Ramstead 2017) and see (Ramstead et al., 2016)).

7.6. Commitment and risk-taking

An ecological perspective on recovery from physical or mental distress seeks to facilitate exploratory behaviour leading iteratively to its extinction. Martha’s fearful disengagement is profound, avoiding most daily activities but also imaginative mental exploration of potential futures. Introducing change will be inherently fearful, and early support with risk-taking within a collaborative relationship based on trust may be critical for initiating recovery (Young et al., 2008). Once over that hurdle, novelty and encountered affordances may continue to build positive motivational influence. This risk-taking, in the face of fear rather than in search of pleasure, can be traced back to our evolutionary ancestors’ exploratory foraging for survival, and is relevant to motivation and behaviour choice in mental illness and trauma recovery (Addicott et al., 2017; Felton et al., 2017). Evidence from engagement in extreme sports offers valuable insight into potential rewards from fearful risk-taking - sensation-seeking plays a minor role, despite participants reporting intense joy and a sense of achievement as they acquire and practice the necessary skills (Willig 2008). Engagement enhances an individual’s sense of self and identity - as competence builds from overcoming fearful vulnerability, participants perceive transformative potential, generating memories that they return to and take strength from (Brymer and Schweitzer 2013).

7.7. Positive emotion

Contemporary therapies for maladaptive outcomes from trauma emphasise positive emotion (Dunn 2017; Allen et al., 2021), which this article’s ecological perspective links to an imagined social future which welcomes and motivates the damaged but recovering self. Positive emotion facilitates behavioural flexibility, the essence of resilience (Kashdan and Rottenberg 2010) – from an evolutionary perspective it opens access to novelty and affordances by motivating exploratory risk-taking in the face of uncertainty, enabling flourishing in times of opportunity. This review emphasises the role of fearful pessimism in maladaptive avoidance of distress, and evidence suggests that the absence of pessimism may be a stronger predictor of positive health outcomes than the presence of optimism (Scheier et al., 2021) reinforcing the importance of education in erasing fear during therapy. Either way, leaning towards hope and away from fear appears critical for inhibiting allostatic imprinting of adversity, resetting sensitised neuro-inflammatory and neuroendocrine responses, and rendering the trauma-constrained neuroimmune system more open to exposure-based cognitive learning (Carver et al., 2010; Fredrickson et al., 2015; Uchida et al., 2018; Judge et al., 2019). The cognitive work of mental imagery can simulate a virtual optimistic future (Ji et al., 2016), enhancing reward (Holmes et al., 2016), influencing self-image (Mancini and Mancini 2018), and positively biasing motivational state (May et al., 2015) facilitating behaviours which will overwrite maladaptive conditioning (Monfils and Holmes 2018; Reddan et al., 2018).

7.8. Self-reinforcing recovery through multidisciplinary therapy

Pain Reprocessing Therapy is one example of a successful multifaceted approach to trauma recovery. It begins with education, encouraging patients to accept that the experience of pain is generated maladaptively within the brain, and helping them reappraise its threat while engaging in recovery behaviours requiring exposure to the feared context(s). Prospective research shows that good symptom improvement is accompanied by restructured connectivity between prefrontal, insular, cingulate and somatosensory cortices (Ashar et al., 2022). This and other therapies such as Emotional Awareness and Expression Therapy, and Acceptance and Commitment Therapy (Lumley and Schubiner 2019), can be viewed as operating in stages: education permits threat reappraisal; emotional awareness with behavioural expression may access and “loosen” fearful neuroimmune inflexibility (Akerblom et al., 2021); commitment to behaviour change enables extinction of maladaptive neural plasticity (Meier et al., 2020; Ashar et al., 2022) (Fig. 7).

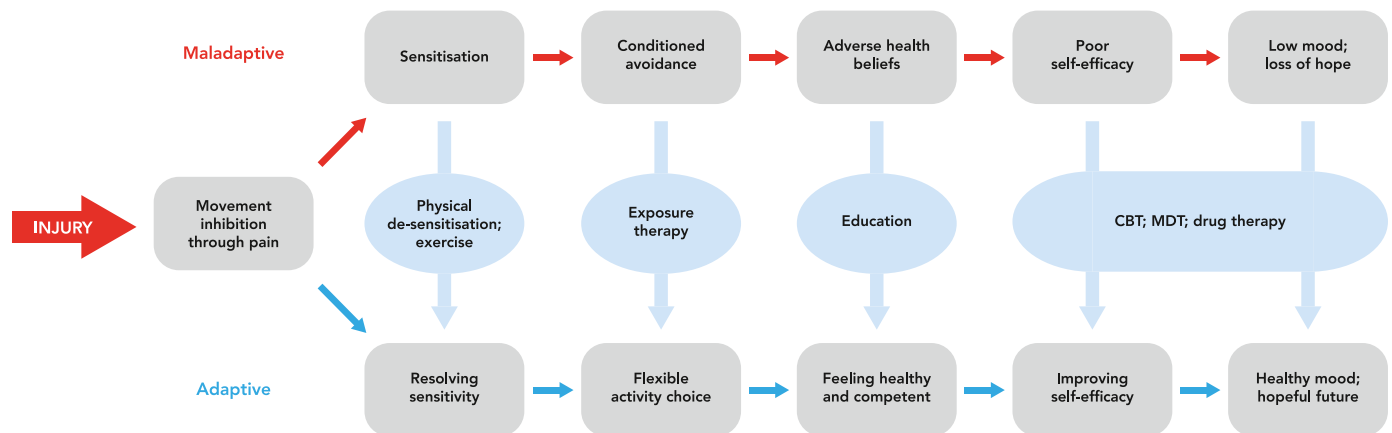


Fig. 7. Therapy should facilitate bridging from an inhibited maladaptive to a self-reinforcing adaptive pathway. The ecological perspective predicts that hopeful adaptive recovery from threat and injury will be a positive process of emotional flourishing (Fredrickson 2004; Fosha and Thoma 2020) - progress may self-sustain within this evolved psychoneuroimmune repertoire as rewarding physical activity replaces fearful avoidance and rebuilds self-efficacy (CBT = cognitive behavioural and related therapies supported by mindfulness training; MDT = multidisciplinary team therapy).

8. Suggestions for future research

This review has explored the sensitising role of prior adversity (allostatic load) and resulting vulnerability; described the divergent and self-reinforcing pathways of adaptive vs. maladaptive recovery as ecological engagement vs. disengagement, emphasising the role of fear in maladaptive responses; illustrated the dynamic motivational continuum guiding decision-making from threat through injury or illness, healing, recuperation, and active recovery; emphasised how anhedonia may facilitate ecological disengagement following physical as well as mental trauma; and shown the essential contribution from physical activity to adaptive recovery from both physical and mental trauma. From this analysis, future conceptual and empirical research with value for trauma recovery may investigate.

- 8.1. The evolutionary foundations of threat-responsive neuro-inflammation, its potential role anticipating injury and accelerating trauma recovery, and the possibility that its pharmacological inhibition may delay recovery.
- 8.2. The role of allostatic prediction in fear-related somatisation, a maladaptive illness response comparable to PTSD (a maladaptive threat response) and nociplastic pain (a maladaptive injury response).
- 8.3. Shared neuroimmune pathways during adaptive-to-maladaptive progression in syndromes of pain/somatisation vs. anxiety/PTSD, exploring cross-domain (mental-physical) sensitisation and modulation of trauma responses.
- 8.4. The origins of anhedonia in somatic dyshomeostasis, acknowledging its ecological influence on behavioural engagement and exploring pharmacological reward manipulation in rehabilitation (see for example the association of nucleus accumbens dopamine disturbance with chronic pain, and enhancement of exploratory behaviour following L-dopa administration in a chronic pain animal model (Borsook et al., 2016; Vachon-Preseu et al. 2016).
- 8.5. The neurobiology of risk-taking in the face of fear, and its potential influence on recovery.
- 8.6. How proprioceptive surveillance influences mood and motivation and its application in choice of recovery behaviours.
- 8.7. Choice of recovery activities following trauma according to ecological value judged within the individual's lifetime neuro-immune narrative.

The principles outlined in this review may support personalised recovery across the full spectrum of outcomes from alienation and trauma - physical disability, mental distress, addiction, and extreme social alienation such as homelessness or imprisonment. Recognising the origins of such symptoms and behaviours in the adversity of social-ecological alienation rather than innate predisposition offers a destigmatising evolutionary perspective, and sign-posts exploratory and purposeful self-valued physical activities for recovery.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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