Experimental Brain Research (2024) 242:783–796
https://doi.org/10.1007/s00221-024-06791-1

REVIEW

Aerobic exercise promotes emotion regulation: a narrative review

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Received: 6 July 2023 / Accepted: 22 January 2024 / Published online: 24 February 2024

Abstract
Aerobic exercise improves the three stages of emotion regulation: perception, valuation and action. It reduces the perception of negative emotions, encourages individuals to reinterpret emotional situations in a positive or non-emotional manner, and enhances control over emotion expression behaviours. These effects are generated via increased prefrontal cortex activation, the strengthening of functional connections between the amygdala and several other brain regions, and the enhancement of the plasticity of key emotion regulation pathways and nodes, such as the uncinate fasciculus. The effect of aerobic exercise on emotion regulation is influenced by the exercise intensity and duration, and by individuals' exercise experience. Future research may explore the key neural basis of aerobic exercise's promotion of emotion regulation.

Keywords Aerobic exercise · Emotion regulation · Prefrontal cortex · Amygdala

Introduction

An individual's emotional state is related closely to their mental and physical health. Emotions can shape human thinking, feeling and behaviour in three stages: perception, valuation and action. Individuals perceive information input from their internal or external environments and evaluate what they perceive, ultimately producing psychological, physiological and behavioural responses (Etkin et al. 2015). They have some control over their own emotions and use different strategies to consciously or unconsciously regulate any stage of emotion generation (McRae and Gross 2020). Emotion regulation can be divided into the same three sequential stages (Fig. 1, Etkin et al. 2015). Specifically, emotions arise from perceiving (P_1) and evaluating stimuli as beneficial or harmful (V_1), leading to a (physical or mental) initial emotional response (A_1)—this is the primary value system in emotion generation. This emotional output A1 is then perceived through emotion regulation (P_2), the secondary value system. Emotion regulation involves re-evaluating the perceived stimulus and its associated initial emotional response (V_2), leading to a regulated response (A_2), which influences subsequent emotional generation. This may involve adjusting perception, cognition, or behaviour—for example, redirecting attention (P_3), reinterpreting the situation (V_3), or modifying the response (A_3). As this regulated response is perceived, it is compared with the targeted state. Emotion regulation iterates until there is a match, highlighting its dynamic aspect in accordance with the extended process model of emotion regulation proposed by Gross (2015). Appropriate emotion regulation strategies help individuals to adjust their emotional states more effectively in response to negative situations and stressful events, whereas impaired emotion regulation can trigger inappropriate emotional responses and increase the risk of developing psychological disorders such as anxiety and depression (Ma et al. 2019).

Many recent studies have established the benefits of aerobic exercise for emotion regulation. Aerobic exercise, also known as endurance training, is characterised by sustained, rhythmic physical activity involving the recruitment of major muscle groups (Chen et al. 2017). It induces metabolic, respiratory, and cardiovascular changes in the practitioner as the heart is required to pump oxygenated blood to the muscles involved (Li et al. 2017). It is noteworthy that both acute and long-term aerobic exercises can exert an influence on

Communicated by Matthew Heath.

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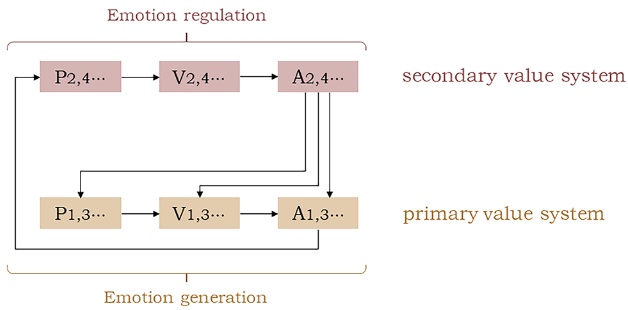

Fig. 1 The three stages of emotion generation and regulation (adapted from Etkin et al. 2015, Fig. 1) *P* perception, *V* valuation, *A* action

human emotions. Acute aerobic exercise, also referred to as short-term or single-session exercise, involves a single bout of physical activity lasting 10–60 min, primarily relying on aerobic metabolism for energy (Zhang and Liu 2019). Long-term aerobic exercise refers to a regular practice of aerobic activities, conducted more than three times a week and sustained for 6 months to a year or longer (Walker et al. 2014). Intervention studies on long-term aerobic exercise typically measure outcomes in months, with a minimum duration of 2 months (Mizzi et al. 2022; Tozzi et al. 2016). Acute aerobic exercise transiently induces changes in endocrine function and brain neural activity, which are progressively accumulated and reinforced with increased frequency and duration of exercise, eventually leading to stable alterations over time.

Empirical studies have demonstrated that aerobic exercise acts on different stages of emotion regulation (Giles et al. 2017; Long et al. 2021; Tartar et al. 2018), enhances emotion regulation performance (Mizzi et al. 2022; Wollenberg et al. 2015), improves mood states (Kim et al. 2022; Schmitt et al. 2019; Thom et al. 2019) and reduces emotional problems (Ligeza et al. 2023; Tozzi et al. 2016). Regular long-term aerobic exercise can enhance the plasticity of certain brain regions (Mendez Colmenares et al. 2021), aid brain development in children and adolescents (Salvan et al. 2021), alleviate declines in cognitive functions such as emotion regulation in elderly adults (Baez-Lugo et al. 2023; Erickson et al. 2015), and treat symptoms of depression and anxiety in clinical populations with mental disorders (Sadeghi Bahmani et al. 2020; Tse 2020). The performance of aerobic exercise increases the release of endorphins and dopamine, producing ‘runner's euphoria’ and diminishing the sensitivity to negative stimuli in the early stages. It optimises the allocation of attentional resources, enhances prefrontal neural activity and functional connectivity centred on the amygdala, downregulates amygdala activation, alleviates negative emotional experiences, enhances individual control over emotional responses, and reduces the regurgitation of thoughts and other emotion regulation tools that are harmful to mental health. However, the mechanisms underlying the benefits of aerobic exercise for emotion regulation need to be explored further. It should be noted that this narrative review exclusively incorporates traditional aerobic exercises such as running and cycling, without extending to strength or resistance training. Resistance training, primarily focusing on muscle coordination, also holds potential for emotional regulation. However, careful consideration must be given to the intensity and rest intervals of strength training, as these variables can significantly alter the intervention outcomes (Bibeau et al. 2010). Furthermore, considering that excessively intense training loads can markedly increase cortisol levels, elevate stress, and suppress the immune system (Mikkelsen et al. 2017), strength training has not been included in our analysis.

Exploring the pathways through which aerobic exercise influences emotion regulation can reveal these mechanisms. This exploration offers new therapeutic options and scientific foundations for developing exercise programs. Such programs aim to enhance emotional stability, support mental health in children and adolescents, and mitigate brain ageing and atrophy in elderly adults. Thus, this narrative review examines current neuropsychological evidence for the mechanisms by which aerobic exercise promotes the three stages of emotion regulation, and summarises the moderating effects and pathways of relevant influencing factors.

Literature search

This narrative review aims to offer a cohesive and narrative synthesis of the empirical evidence concerning the mechanisms through which aerobic exercise enhances emotion regulation. Given the broad nature of this objective, it is impractical to conduct a review that covers all empirical findings exhaustively. Therefore, to ensure a thorough and impartial selection of literature, we implemented the subsequent methodology: (a) we conducted comprehensive queries in databases such as PubMed, Google Scholar, and Web of Science, employing key terms like 'exercise', 'aerobic exercise', 'physical activity', 'emotion', 'emotion regulation', and 'mental health' in our search for pertinent literature. (b) Our search strategy was further refined and directed by consulting widely recognised review papers and meta-analyses that focus on emotion regulation and aerobic exercise. (c) The emphasis was placed on studies that demonstrated consistent results across various neuroscience methodologies, including electrophysiology, functional near-infrared spectroscopy (fNIRS), and functional magnetic resonance imaging (fMRI), particularly those involving human subjects. This narrative review also considers insights from questionnaire-based and behavioural studies. (d) In terms of original experimental research, we primarily referenced publications from the past decade. However, for theoretical perspectives, we included older, highly cited articles as well.

The promotion of aerobic exercise at different stages of emotion regulation

Perception phase

In the process of emotion generation, individuals first perceive salient information from the internal or external environment, and then process and evaluate it. At this stage, individuals can reduce their susceptibility to negative emotions by limiting the allocation of attention to negative emotional stimuli, thereby reducing the input of negative valence information at its source (Etkin et al. 2015). This process directly reduces the cognitive load during subsequent emotion processing, conserving cognitive resources for later stages of emotion regulation.

Because the perception phase occurs early in emotion generation and regulation, researchers have explored it using high-temporal-resolution electroencephalography (EEG) with the event-related paradigm. Early event-related potential (ERP) components (e.g., N1 from parietal lobe and N2 from central prefrontal cortex) characterise attentional recruitment and capture with greater attention to a target inducing larger wave amplitudes (Kumar et al. 2009). Studies have revealed that aerobic exercise helps to reduce the perception of and susceptibility to negative emotions by altering the level of brain activity to slow attentional alertness to negative stimuli (Qiu et al. 2019; Zelenski and Larsen 1999). In addition, human physiological motor levels are elevated during aerobic exercise; high physiological arousal prior to the experience of a negative emotional stimulus is likely to buffer its perception (Edwards et al. 2017). Evidence indicates that both acute (20–30 min, moderate intensity, 60–69%HR_{max}) and chronic (> 3 times/week, at least 30 min, last more than 6 months) aerobic exercise effectively reduces the amplitude of N1 in parietal cortex and N2 components in central PFC when individuals are exposed to negative emotional stimuli, and notably, such effects are absent in electrophysiological responses to neutral stimuli (Hwang et al. 2019; Qiu et al. 2019; Zhang et al. 2022). This highlights the role of aerobic exercise in modulating neural reactions to negative emotions, emphasising a selective impact dependent on the emotional nature of the stimulus. The reduction of early ERP amplitudes induced by negative stimuli after aerobic exercise suggests that aerobic exercise helps to reduce the early allocation of attention to negative emotional cues and attenuates perceptual processing, reducing resource consumption during the perception of negative emotional stimuli and thus freeing up more attentional resources for subsequent cognitive processes.

In addition, aerobic exercise can indirectly bias attention toward positive and away from negative stimuli by improving mood. According to the mood congruency hypothesis, individuals' attention is biased toward the perception of mood-congruent emotional stimuli (Chen et al. 2019), such that a positive mood increases attentional preference for positive valence stimuli and decreases the perception of and reactivity to negative valence stimuli (Voelkle et al. 2014). The late positive potential (LPP) is a classic ERP measure of emotional neuro-response, as its wave amplitude is related to emotionally salient stimuli (Schupp et al. 2006). Aerobic exercise (running and cycling) induces increased dopamine and endorphin release, elevating sympathetic arousal and improving mood (Basso and Suzuki 2017; Tartar et al. 2018), which in turn leads to increased and decreased neural responses to positive and negative potentiated stimuli, respectively. This process is evidenced by significant decreases and increases in the LPP wave amplitude when viewing negative and pleasant pictures, respectively (Ligeza et al. 2023; Tartar et al. 2018).

Valuation phase

During the valuation phase of emotion regulation, individuals positively reappraise emotional situations, attaching new meaning to stimuli (e.g. imagining positive outcomes, denying the authenticity of the affective picture) and thus effectively changing subsequent emotional trajectories (Goldin et al. 2008). This process is known as cognitive reappraisal and involves complex cognitive processing such as information integration, evaluation and switching (Perchtold-Stefan et al. 2020). Damage to areas such as the orbitofrontal cortex (OFC) and dorsolateral prefrontal cortex (dlPFC) can lead to the dysregulation of this function (Falquez et al. 2014; Rudebeck et al. 2013). Cognitive reappraisal, aiming to enhance the emotional experience, involves a network of multiple cortical and subcortical areas, notably the prefrontal and parietal lobes, which function in a top-down manner to regulate activity levels in areas responsible for emotional responses, especially the amygdala (Kohn et al. 2014). For example, single-pulse TMS was employed to increase the activity of the ventrolateral prefrontal cortex, leading to a significant and specific reduction in the activation level of the amygdala (Sydnor et al. 2022). Additionally, a white matter pathway, with fibre density correlating with the extent of amygdala activity alteration, was identified to link the prefrontal cortex and the amygdala (Sydnor et al. 2022). Aerobic exercise has been shown to improve cognitive reappraisal efficiency. This improvement is attributed to the positive impact of aerobic exercise on the function and structure of the prefrontal cortex, the enhanced connectivity between the amygdala and other brain regions, and the strengthened integrity of white matter fibre tracts in the associated neural pathway (Belcher et al. 2021; Chen et al. 2019; Ge et al. 2021; Schmitt et al. 2020).

During cognitive reappraisal, resources in the prefrontal region need to be mobilised to inhibit amygdala activity (Drabant et al. 2009; Kohn et al. 2014), and prefrontal oxyhemoglobin concentrations have been found to increase with aerobic exercise intensity (Tempest and Parfitt 2017). Increased prefrontal neural activity promotes cognitive reappraisal, and increased dlPFC activation induced by moderate cycling lasting for 30 min predicts better behavioural performance during the valuation stage (Zhang et al. 2021). In addition, the prefrontal grey matter volume is associated positively with the cognitive reappraisal ability, and individuals with prefrontal grey matter lesions have impaired cognitive reappraisal performance (Falquez et al. 2014). Long-term aerobic exercise has been found to significantly increase the grey matter volume in areas such as the inferior frontal gyrus (IFG) (Colcombe et al. 2006), and the duration of high-intensity aerobic exercise was associated positively with the prefrontal grey matter volume in adolescents (Salvan et al. 2021). IFG, part of the dorsolateral prefrontal cortex, plays a role in detecting affective arousal and processing semantics (Moore et al. 2016). The cortical thickness of the IFG correlates with enhanced semantic processing capabilities, and a reduction in its integrity may impede the ability to regulate arousal levels (Falquez et al. 2014; Urgesi et al. 2016). Consequently, an increase in IFG grey matter volume could potentially improve valuation efficiency. Furthermore, cognitive reappraisal is associated with grey matter volume in the frontal cortex, notably in regions such as the middle frontal cortex and the left superior frontal cortex (Moore et al. 2016). Individuals with regular aerobic exercise habits are more likely to engage in emotional regulation during the valuation phase and can more effectively reduce negative emotions (Giles et al. 2017; Perchtold-Stefan et al. 2020). Thus, long-term aerobic exercise likely enhances emotion regulation during the valuation stage by increasing the prefrontal grey matter volume; however, no study has directly explored this causal relationship.

The effectiveness of the prefrontal lobe's inhibition of neural activity in the amygdala depends not only on the activation of the prefrontal region, but also on the presence of adaptive functional connections between this region and the amygdala. Sonkusare et al. (2022) showed that a bidirectional effector connection exists between the human amygdala and the prefrontal lobe. This pathway is central in the valuation phase of emotion regulation (Banks et al. 2007), and aerobic exercise can significantly increase its connectivity. Acute aerobic exercise directly enhances connectivity from the OFC to temporal cortical areas such as the amygdala, and this change is associated strongly with improved emotion experience (Ge et al. 2021; Maurer et al. 2022). The amygdala is the central region for emotion, where the bottom-up processing of emotionally salient stimuli regulates neurophysiological responses through feedback projections to other brain regions (Sergerie et al. 2008; Šimić et al. 2021). In addition to the prefrontal–amygdala pathway, aerobic exercise protects emotional networks and positively regulates other functional connections centred on the amygdala. For instance, the insula receives information input from the amygdala (Muhtadie et al. 2021), the insula–amygdala pathway characterises the evaluation of positive emotional stimuli such as happiness, which can be reinforced by aerobic exercise (Y.-C. Chen et al. 2019), and the increase in amygdala–insula connectivity after exercise correlates positively with positive emotional changes (Schmitt et al. 2020).

Changes in connectivity induced by acute aerobic exercise induce structural changes in the brain as the number of workouts increases. The increased integrity of white matter fibre bundles, such as the uncinate fasciculus, after chronic aerobic exercise may provide anatomical support for the changes in functional connectivity described in the previous paragraph. The uncinate fasciculus is a joint fibre bundle of the OFC, hippocampus and amygdala (Šimić et al. 2021) that provides bidirectional information transfer among the OFC, medial PFC and anterior temporal lobe (Coad et al. 2020) and functions in the evaluation phase of emotion regulation (Zuurbier et al. 2013). It may be the fundamental anatomical structure for functional connectivity between regions such as the PFC and amygdala. After 8 months of daily aerobic exercise (40 min), obese adolescents had significantly greater fractional anisotropy and less radial diffusivity in the bilateral uncinate fasciculus, indicating deeper myelination and improved white matter integrity, than did those who did not engage in physical exercise (Schaeffer et al. 2014). Thus, long-term aerobic exercise may enhance emotion regulation during the valuation phase by enhancing the integrity of the uncinate fasciculus and inducing changes in potential effector connections in pathways such as the prefrontal–amygdala pathway, but this process needs to be confirmed by empirical studies.

Action phase

The action phase represents the later stage of emotion regulation, where individuals have fully perceived both internal and external environments and appraised the emotional stimuli, with their emotional response tendencies being fully formed. Thus, individuals can only regulate their emotions by modifying emotional responses in accordance with the context, or by suppressing emotional expression. Specifically, this can be categorised into expression suppression and socio-emotional behavioural control. Aerobic exercise can enhance an individual's performance in action phase of emotion regulation.

Expression inhibition involves the deliberate suppression of emotional expression, integrating interoception–proprioception and social awareness, and is characterised by the inhibition of bodily movements, facial expressions and other emotional overt expression (Gross 1998, 2002; Muhtadie et al. 2021). Expression inhibition is a type of general inhibition that engages multiple brain regions, particularly involving the frontoparietal cognitive control network (Goldin et al. 2008; McRae and Gross 2020). This process is notably characterised by the activation of the dorsolateral prefrontal cortex and the inferior parietal lobule, as reported in numerous studies during the suppression of expressions (Anderson et al. 2021; Dörfel et al. 2014; Sikka et al. 2022). Although this strategy requires significant cognitive effort and does not alleviate the subjective emotional experience, it may be adaptive in specific situations (Sikka et al. 2022), such as when a doctor needs to control his or her facial expression when viewing a gory scene. Aerobic exercise is increasingly recognised for its positive impact on expression inhibition, a key aspect of general inhibitory function. This beneficial influence, extensively documented in research, includes enhancements to inhibitory processes (Ishihara et al. 2021). Specifically, acute aerobic exercise activates critical brain regions like the dorsolateral prefrontal cortex (dlPFC), thereby boosting general inhibitory control efficiency (Zhang and Liu 2019). In parallel, sustained, regular aerobic exercise fortifies the integrity of white matter fibre tracts linked to the prefrontal cortex. This reinforcement of top-down control systems also positively alters the functional plasticity of the frontoparietal regions, as evidenced by various studies (Belcher et al. 2021; Lu et al. 2018; Mendez Colmenares et al. 2021; Yanagisawa et al. 2010). Furthermore, long-term aerobic exercise not only increases the grey matter volume in the frontal-parietal region (Salvan et al. 2021) but also correlates with enhanced inhibitory control, as larger grey matter volumes have been shown to predict better inhibitory capabilities (Chen et al. 2015). Additionally, the cardiovascular health improvements from long-term aerobic exercise, which enhance brain oxygenation and glucose delivery, play a crucial role in boosting neurotransmitter efficacy and thereby improving inhibitory control efficiency (Kramer et al. 2006; McMorris 2016). The facilitation of inhibitory control by aerobic exercise is likely to encompass the control of emotionally expressive behaviours. For example, aerobic exercise enhances men's inhibitory control of facial expressions when exposed to negative (fearful face) stimuli, based on the deactivation of the nucleus accumbens, which is involved in top-down emotion processing (Anderson et al. 2021; Ochsner et al. 2009; Schmitt et al. 2019).

Socio-emotional behavioural control is an emotion regulation strategy characterised by the automatic tendency to overcome the inclination toward positive stimuli and avoidance of negative stimuli during emotional responses (Kaldewaij et al. 2021). Occupations such as policing and firefighting require the use of this strategy to overcome the automatic risk-avoidance response and enter dangerous situations proactively. This strategy involves multiple processes such as response tendency inhibition and action selection and preparation, and requires the recruitment of resources in the cognitive and motor control areas of the brain, such as the frontal pole, dlPFC, and parietal and sensorimotor areas for the control of conflict with neural input from the amygdala (Bramson et al. 2018; Volman et al. 2011). As previously mentioned, since aerobic exercise enhances both the function and structure of the prefrontal and parietal regions, it is considered an effective method for improving the socio-emotional behavioural control.

In integrative terms, how aerobic exercise affects the aforementioned three phases of emotion regulation is illustrated in Fig. 2. Specifically, during the early perception phase, aerobic exercise can enhance individual arousal levels, acting as a buffer for the perception of negative emotions, reducing susceptibility to negative emotions. Post-exercise improvements in mood orient attention towards positive stimuli while reducing the capture of attention by negative stimuli. Moreover, in this phase, the facilitative effect of aerobic exercise on emotional regulation operates independently of its benefits on executive functions, as early emotional stimulus perception (N1, approximately 100-150 ms) occurs before cognitive processing of the stimulus information (Zhang et al. 2022). In the mid-term evaluation phase, aerobic exercise boosts frontal activation and connectivity in emotional regulation pathways, such as the modulation of the amygdala by the prefrontal lobe. This also leads to increased plasticity in the grey and white matter of brain regions involved in cognitive reappraisal, like the unciform fasciculus, thereby enhancing the ability to cognitively reappraise and alter emotional trajectories following exposure to negative stimuli. In the late action phase, aerobic exercise impacts brain areas like the frontoparietal control network, crucial for expression inhibition, thus enhancing an individual's inhibitory control efficacy and preventing emotionally driven, contextual inappropriate responses. Additionally, in both the valuation and action phases, improvements in executive function following aerobic exercise may mediate enhancements in emotional regulation performance. Specifically, during the valuation process, individuals need to maintain reappraisal goals in working memory, inhibit repetitive thoughts about negative antecedent events and negative self-reflections, and swiftly shift from negative interpretations of emotional events to positive ones. Furthermore, the action phase demands individuals to exert inhibitory control over emotional response outputs.

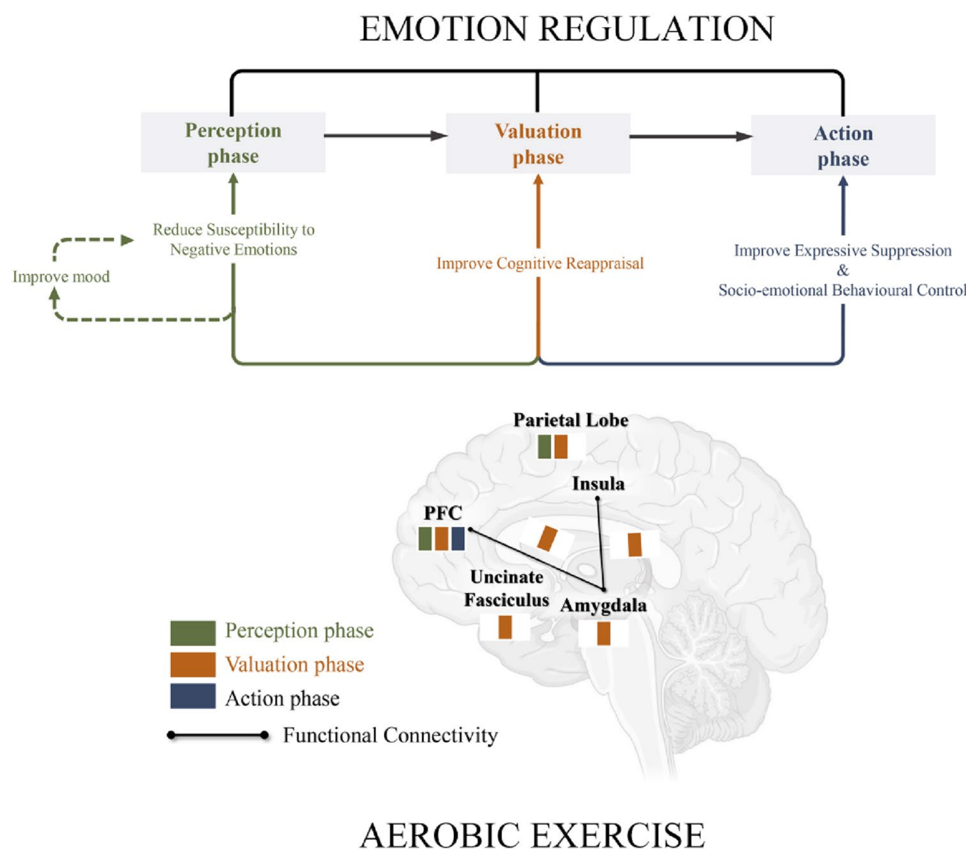

Fig. 2 The impact of aerobic exercise on emotional regulation and potential mechanisms

Factors influencing aerobic exercise for emotion regulation

Exercise intensity

The association between the intensity of aerobic exercise and its impact on emotion regulation follows an inverted U-shaped curve, with numerous empirical studies consistently demonstrating that moderate-intensity exercise is most beneficial for emotion regulation (Ligeza et al. 2023; Meyer et al. 2016).

At the physiological level, moderate-intensity aerobic exercise can increase the secretion of catecholamines, such as dopamine, and constrain serotonergic (5-HT) neural activity, enhancing emotional processing and stress resistance (Greenwood 2019). This exercise intensity also elevates plasma endorphin levels, inducing feelings of pleasure and positive emotional experiences. Additionally, there is an increase in endogenous cannabinoids, which helps alleviate anxiety and other negative emotions (Dinas et al. 2011; Mikkelsen et al. 2017). Furthermore, at this intensity, carbon dioxide partial pressure and cerebral blood flow remain consistent with resting levels (Matta Mello Portugal et al. 2013). The results of experiments show that, when the heart rate (HR) is maintained at 60–70% of the maximal heart rate (HR_{max}), the early perceived sensitivity to negative stimuli is reduced, emotion regulation is increased, emotion recovery is accelerated, inhibitory control capacity improved, and negative emotions such as depression are effectively relieved (Bernstein and McNally 2017, 2018; Ge et al. 2021; Yanagisawa et al. 2010; Zhang et al. 2022).

Lower intensity exercises, such as walking which induces heart rates below 60% of the maximum heart rate (HRmax), do not appear to affect subjects' ability to regulate emotions like sadness, anger, or anxiety over a period of 15 min (Edwards et al. 2018). In contrast, jogging for the same duration has been shown to improve these negative emotional states (Edwards et al. 2018). In addition, individuals engaging in very low-intensity exercise (~40% HR_{max}) have demonstrated an amplified amygdala response to fear compared to happiness (Y.-C. Chen et al. 2019). Conversely, higher intensity activities (~75% HR_{max}) such as running have been observed to elicit the opposite effect (Chen et al. 2019).This is likely because both endorphin and catecholamine release post-exercise are intensity-dependent, with effects amplifying at higher exercise intensities (Ligeza et al. 2021). Low-intensity exercises may not induce sufficient physiological changes to significantly induce emotional cognitive changes. Additionally, in high-intensity exercises exceeding maximal oxygen uptake, there is a tendency for hyperventilation, leading to reduced partial pressure of carbon dioxide in the blood (Matta Mello Portugal et al. 2013).

This results in decreased cortical blood oxygen levels, particularly in the prefrontal cortex (Rooks et al. 2010). Such high-intensity exercise, often perceived as threatening, can induce negative emotional states. These exercise intensities, particularly when inducing heart rates of around 87% of HRmax, have been found to augment the perception of stress (Paolucci et al. 2018). However, in a minority of cases, particularly among athletes or subjects with higher levels of fitness who regularly engage in aerobic training, there is a significant improvement in cognitive reappraisal following high-intensity (~ 96%HR_{max}/average heart rate of 187 bpm) intervention (Schmitt et al. 2019). This aspect will be further discussed in Subsection 4.3.

Exercise duration

Combining the paradigms and findings of current experimental studies, the relationship between emotion regulation performance following acute aerobic exercise and the duration of exercise also follows an inverted U-shape pattern. Notably, a single session of aerobic exercise lasting between 20 and 30 min has been shown to briefly enhance emotion regulation capabilities. Specifically, cycling by ergometer for 20–25 min enhanced the efficiency of individuals' emotion regulation when viewing negative valence pictures (50%-75%HR_{max}) (Long et al. 2021), and alleviated negative emotional feelings (60%-70%HR_{max}) (Kim et al. 2022). Thirty minutes of aerobic training helped to alleviate neurophysiological responses to negative stimuli and enhance cognitive reappraisal (60%-69%HR_{max}) (Zhang et al. 2021). Aerobic exercise for < 10 min did not enhance subjects' emotion regulation when viewing negative emotional videos and pictures, and exercise for > 75 min had a negative effect on emotional states (Reed and Ones 2006).

During exercise, the synthesis and release of neurotransmitters and neurotrophic factors, as well as the transport of nutrients from the peripheral blood through the blood–brain barrier into the brain, take time (Matta Mello Portugal et al. 2013; Rojas Vega et al. 2006). As the availability of brain glucose and dopamine increases over the course of an exercise session, this enhances the overall activity level of the brain. On one hand, exercise durations that are too short produce minimal effects, insufficient to reach statistical significance. On the other hand, overly extended exercise sessions can lead to a reduction in cerebral blood flow by up to 20%, diminishing neural processing efficiency (Nybo et al. 2002). This decrease is not conducive to emotion regulation strategies like cognitive reappraisal and expression inhibition that require cognitive load.

Exercise experience

Exercise experience is an important factor influencing the effect of aerobic exercise interventions on emotion regulation; it modulates the thresholds of the inverted U-shaped curves for exercise intensity and acute exercise duration. Subjects with long-term running experience (weekly running distance more than 30 miles, including at least one run exceeding 9 miles) had significantly elevated emotion regulation performance after 90 min of running (Giles et al. 2018). Those who exercised regularly (3 times per week, with each session lasting at least 45 min) had reduced negative emotional responses and increased positive emotional states after high-intensity exercise (inducing HRs of 90–96% HR_{max}, 30 min) (Schmitt et al. 2019, 2020). The emotional improvements induced by high-intensity (88%HR_{max}, 24 min) aerobic exercise have been found to be greater for physical active individuals (exercise 3–4 times/week) (Ligeza et al. 2021). This may be due to such groups having a higher adaptation to exercise intensity, or possibly because their cerebral cortex requires less metabolic demand, as evidenced by lower cortical oxygenation levels during moderate-intensity exercises (Rooks et al. 2010). During high-intensity exercise, endoreceptive information input is reduced and the prefrontal oxygenation level remains high in individuals with exercise experience, whereas the prefrontal oxygenation level declines to the resting baseline in those without such experience (Rooks et al. 2010).

Acute aerobic exercise versus chronic exercise

The mechanisms through which acute and chronic aerobic exercise impact emotion regulation show both differences and connections. Acute aerobic exercise enhances arousal, brain activation, and connectivity, temporarily boosting the synthesis and release of neurotransmitter and neurotrophic, leading to an immediate sense of well-being and reduced sensitivity to negative stimuli. Notably, the effects of acute exercise extend beyond the activity period. For instance, heightened neural activity in the frontoparietal region persists up to 15 min post-exercise (Schneider et al. 2010). However, these effects are ephemeral, as indicated by a decrease in prefrontal cortex oxygenation shortly after exercise cessation (Fumoto et al. 2010). Additionally, while aerobic exercise elevates brain-derived neurotrophic factor (BDNF), crucial for emotional health (Ballesio et al. 2023), this increase is not sustained post-exercise, with levels returning to baseline within 15 min (Rojas Vega et al. 2006). Studies focusing on acute aerobic exercise generally measure emotional regulation performance immediately after the exercise intervention. However, there is no clear definition or consistency in the interval between the end of the exercise and the start of the task/questionnaire. Consequently, this narrative review cannot precisely specify how long the facilitative benefits of aerobic exercise may persist. Based on the duration of emotional regulation tasks and changes in endocrine and brain activities, it is principled to assume that these benefits should last at least 20 min. Moreover, the exploration of emotional regulation performance during acute exercise remains sparsely investigated.

Changes in neuromodulation and neural activity induced by a single session of aerobic exercise continue to consolidate, and an increase in exercise/training frequency over time produces homeostatic adaptations and plastic changes in the human brain (Weng et al. 2017). Chronic aerobic exercise exerts a more stable influence on emotion regulation. Typically, post-intervention assessments are not conducted immediately following the final exercise session, to avoid the immediate effects of the last exercise bout in long-term studies. Research has indeed found a strong correlation between long-term aerobic exercise and enhanced cognitive reappraisal abilities (Mizzi et al. 2022). Chronic exercise improves brain plasticity, for instance, by enhancing connectivity in networks centred around the hippocampus and amygdala (Schmitt et al. 2020; Tozzi et al. 2016), increasing the integrity of white matter fibre tracts connecting the prefrontal cortex and amygdala (Schaeffer et al. 2014), and elevating dopamine levels in the medial prefrontal cortex (C. Chen et al. 2017), which are crucial for emotion regulation (Phillips et al. 2003). Additionally, long-term exercise provides neuroprotective effects, resulting in lower cortisol levels during stress and fewer reported difficulties in everyday emotional regulation (Matta Mello Portugal et al. 2013).

Theoretical explanations for aerobic exercise's promotion of emotion regulation

The arousal hypothesis

The arousal hypothesis, originally proposed by Davey (1973), holds that exercise, as an organismal stressor, enhances neurological, physiological and psychological arousal (Tartar et al. 2018), which diminishes the degree of negative emotion perception and response (Edwards et al. 2017). Increased arousal also strengthens neural activity in the PFC, optimising the recruitment and allocation of mental resources (Audiffren 2009; Byun et al. 2014; Lambourne and Tomporowski 2010). Cognitive reappraisal and expression suppression depend strongly on the top-down regulation of prefrontal cognitive control (Buhle et al. 2014; Sikka et al. 2022). High levels of prefrontal activation can enhance general cognitive control and contribute to the down-regulation of amygdalar activity and the inhibition of limbic movements, thereby enhancing the efficiency of emotion regulation during the valuation and action phases and alleviating negative emotional experiences (Miller and Cohen 2001; Zhang et al. 2021). The arousal hypothesis thus explains the benefits of aerobic exercise for all three phases of emotion regulation, and has been used to explain the mood-enhancing effects observed in many acute aerobic exercise intervention studies (Y. Zhang et al. 2022).

The dual-mode theory

The dual-mode theory was first proposed by Yerkes and Dodson (1908), who found that the relationship of mouse behaviour to arousal took the form of an inverted U-shaped curve. It holds that cognitive performance is poor with low and high levels of organismal arousal, and that behavioural performance is optimal with moderate arousal. As exercise can increase arousal levels, researchers have adopted this theory to explain its effects on cognitive performance (Kamijo et al. 2007). When the intensity of aerobic exercise falls below the ventilatory threshold, physiological arousal is moderate and euphoria and neural activity in the PFC (the main source of input to the amygdala) increase; this process alleviates negative emotions and suppresses emotional responses in the valuation and action phases of emotion regulation. When exercise intensity approaches the respiratory compensatory point, excessive arousal and neural signal noise consume limited cognitive resources. Moreover, a decrease in the PFC oxyhemoglobin concentration weakens the top-down prefrontal regulation of emotion, and increased subcortical reinforcement of endoreceptive information afferents triggers negative emotional responses (Ekkekakis 2003; Rooks et al. 2010; Tempest and Parfitt 2017). The dual-mode theory further proposes an inflection point in the positive association between emotion regulation and exercise-induced arousal. This theory is equally applicable to explanations of the benefits of both acute and chronic aerobic exercise for the three stages of emotion regulation. Particularly since most aerobic exercise intervention studies opt for moderate intensity as the exercise load, the dual-mode theory provides robust support for this choice of exercise intensity (Giles et al. 2018).

Neuroplasticity

The theory of neuroplasticity emphasises that repetitive experiences and lifestyles lead to specific changes in brain plasticity (Erickson et al. 2012). Chronic aerobic exercise increases brain-derived neurotrophic factor levels, enhancing and consolidating neurogenesis and synaptic plasticity in some brain structures (Jia et al. 2022). Changes in structural brain plasticity support functional changes, thereby enhancing cognitive control, emotional states and behavioural performance (Budde et al. 2016). Chronic aerobic exercise helps to increase grey matter volumes in areas such as the frontoparietal lobe and to enhance the integrity of white matter fibre tracts such as the uncinate fasciculus, which play roles in emotion processing and regulation (Malezieux et al. 2023; Mendez Colmenares et al. 2021; Salvan et al. 2021; Schaeffer et al. 2014). It also increases the strength of connectivity between brain regions related to emotion regulation, reducing emotion regulation impairment (Schmitt et al. 2020; Tozzi et al. 2016). As brain neuroplastic changes require sustained exercise over time, this theory is commonly used as the theoretical foundation for studies on long-term exercise interventions (Hwang et al. 2019).

Other theories and hypotheses

In addition to the previously mentioned hypotheses, cognitive theories like self-efficacy theory and the cardiovascular fitness hypothesis also offer explanations for the effects of exercise on emotion regulation. These theories suggest that regular physical activity boosts self-efficacy, thereby improving well-being and reducing negative emotions (McAuley and Courneya 1992; Rudolph and Butki 1998), and that increased maximal oxygen uptake from 6 months aerobic training (3 times/week) enhances the connectivity of emotion regulation pathways, improving emotional states (Maurer et al. 2022). Few studies have delved into the neural basis of the self-efficacy theory, only establishing a correlation between increased self-efficacy and emotional improvement (Ge et al. 2021; Tse 2020). Similarly, the cardiovascular fitness hypothesis, as primarily evidenced in Maurer et al.'s study (2022), suggests a link between increased VO_2peak and improved emotion regulation pathways and emotional states. However, this hypothesis is yet to be substantiated with behavioural evidence, warranting further exploration and discussion in the field. Moreover, reviews on exercise interventions infrequently address these hypotheses, resulting in their limited examination in this narrative review.

On a physiological level, the neurotransmitters, the endorphin hypothesis and the hypothalamic–pituitary–adrenal (HPA) axis serve as theoretical bases for explaining how exercise enhances emotion regulation. These hypotheses explore the effects of exercise on brain neurotransmitters, opioid components, inducing feelings of pleasure and calmness, and reducing the HPA axis response to stress and negative stimuli, thereby lessening the perception of negative emotions (Mikkelsen et al. 2017). However, direct experimental validation of these hypotheses is challenging. Invasive studies on animal brains and analyses of human peripheral blood do not accurately reflect the true state within the human brain. Furthermore, blood plasma collection, being highly invasive, can itself influence emotions.

Summary and future directions

In summary, studies have provided abundant evidence for the effects of aerobic exercise on emotion regulation; appropriate aerobic exercise, in terms of intensity, duration and experience, contributes to such regulation. Many researchers have used the arousal hypothesis and/or dual-mode theory to explain the positive effects of acute aerobic exercise on emotion regulation, and the neuroplasticity theory to explain such effects of long-term aerobic exercise. In addition, the mechanisms underlying the benefits of aerobic exercise on emotion regulation need to be explored further, with the incorporation of more theoretical frameworks to assemble evidence from multiple perspectives.

Neural mechanisms

During the perception phase of emotion regulation, aerobic exercise reduces the intensity of the perceived attentional bias toward negative emotional stimuli by increasing arousal and stimulating euphoria, conserving more cognitive resources for subsequent emotion regulation. As this phase occurs early in emotion regulation, the effects of aerobic exercise on it have been studied using high-temporal-resolution EEG. However, the spatial accuracy of EEG is low, making it difficult to precisely localise neural activity in the brain; techniques such as functional magnetic resonance imaging and experimental paradigms such as point detection could be employed for this purpose. During the valuation phase, aerobic exercise has been proposed to significantly enhance cognitive reappraisal by increasing prefrontal neural activity, enhancing functional connectivity between the amygdala and other brain regions, and decreasing the resting-state activation of the default mode network, thereby increasing the structural plasticity of emotion regulation networks. The key role of the hippocampus in the reappraisal phase has not received sufficient research attention. The hippocampus is a key node in the limbic system involved in the processing of fearful and anxious emotions (Malezieux et al. 2023), and the degree of synchrony between the hippocampus and amygdala represents an individual's emotional state (Kirkby et al. 2018) and plays a role in the appraisal and expression control aspects of emotion regulation (Belcher et al. 2021). Hippocampal damage can reduce an individual's ability to regulate emotions (Guzmán-Vélez et al. 2016). Furthermore, the hippocampal volume is subject to exercise-dependent changes throughout the human lifespan; aerobic exercise significantly increases this volume and enhances connectivity within the hippocampus and between the hippocampus and brain regions such as the prefrontal lobe (Li et al. 2017; Weng et al. 2017). Thus, further exploration of the role of the hippocampus in the enhanced efficacy of emotion regulation caused by aerobic exercise is needed.

Researchers have focused on aerobic exercise's positive effects on the perception and valuation phases of emotion regulation, giving less attention to its effects on the action phase. In this phase, aerobic exercise may enhance general inhibition by modulating the function of emotion-processing brain regions, such as the frontoparietal executive control area and the nucleus accumbens, thereby enhancing emotion-regulating behaviour; however, direct evidence for such an effect remains lacking. Additional research employing exercise interventions, experimental paradigms such as the approach-avoidance task and magnetic resonance imaging is needed to verify causal relationships in the action phase. In addition to subjective reports, researchers can use more objective techniques such as facial electromyography and facial expression modelling analysis to monitor individuals' responses to emotional stimuli, including expression suppression. Furthermore, despite the broad overlap between brain areas in which movement-dependent changes occur and those activated during emotion regulation, researchers have focused on the PFC and amygdala, neglecting potentially key brain networks and regions such as the hippocampus. Additional research is needed to comprehensively explore the key brain nodes in which aerobic exercise enhances emotion regulation, refine our understanding of the underlying neural mechanisms, and provide empirical evidence for further theory development.

Optimal exercise interventions

Based on a synthesis of previous findings, aerobic exercise that induces HR maintenance at 60–70% HRmax (moderate intensity) for 20–30 min may be most helpful for emotion regulation. Single aerobic exercise sessions transiently alter brain activation and enhance emotion regulation, and long-term regular aerobic exercise has lasting effects on structural and functional brain plasticity, also enhancing emotion regulation. The efficiency of emotion regulation increases with the number of sessions/days of regular aerobic exercise. The results of one study suggest that the emotion regulation–enhancing effect of long-term regular aerobic exercise begins to emerge after approximately 8 weeks (Mizzi et al. 2022). Exercise experience mediates this effect; individuals with regular exercise habits experience better emotion regulation after intense, prolonged aerobic exercise.

The benefits for emotion regulation of different exercise intensities and session durations in individuals with long-term exercise experience, and the effects of aerobic exercise on emotion regulation in diverse populations, need to be explored further. Most studies have been performed with young adults (i.e. college students), and few studies have included children, older adults or individuals with mood disorders (Ligeza et al. 2023; Mizzi et al. 2022). As school-aged children should engage in 60 min of moderate–vigorous physical activity per day (Salvan et al. 2021), exercise interventions for children should be more frequent, longer, more interesting and more varied. Interventions for older adults should be tailored to their exercise experience; for example, they could begin with short, low-intensity walking and gradually increase in duration and intensity thereafter (Erickson et al. 2011). Regular aerobic exercise has been shown to be an effective non-pharmacological treatment for mental disorders; as clinical affective disorder groups may have varying degrees of somatisation; exercise loads should be adjusted according to these patients' aerobic fitness. In summary, future research should be performed with more heterogeneous subject groups to provide a scientific basis for tailored exercise prescriptions.

Author contributions XJ and CZ were responsible for the review outline and design. XW and TL drafted the manuscript. XJ and CZ provided critical revision of the manuscript.

Funding The preparation of this review was supported by the National Natural Science Foundation of China (No.32200893).

Data availability Not applicable. There are no data generated or analysed during this narrative review.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Ethics approval and consent to participate Not applicable. This paper is a narrative review, and no subjects were recruited, so ethical approval and informed consent are not required.

Consent for publication All authors agreed to the publication of this narrative review.

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