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NEURAL PATHWAYS INVOLVED IN EMOTIONAL REGULATION AND EMOTIONAL INTELLIGENCE

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Abstract

Emotional regulation and associated processing cumulateaccumulate to develop and determine the emotional intelligence of an individual. Both emotional regulation and emotional intelligence are prominent determinants of how individuals navigate social as well asand personal aspects of their daily lives. Neural pathways connecting different brain regions and circuits play a crucial roleroles in processthe modulation of emotional responses. These pathways are explored further duringin this review, and the article goes over the neurological processes involved in emotional processing and reception of emotional stimulusstimuli from the surroundings are reviewed. The neural correlations of emotional regulation and emotional intelligence in the limbic system isare detailed along with the process flow of emotional stimulusstimuli across different age groups ranging from adolescentadolescents to older adults. The constructs of emotional regulation and emotional intelligence are essential tofor producing appropriate emotional responses, developing stronger relationships, and balancing the mental well-being of individuals.

Keywords: Emotional Regulation, Emotional Intelligence, Neural Pathways, Emotional Responses, Precision Medicine, Biomedical

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1. Introduction

Emotions result from small changes in a person's physiology that arise from generating an appropriate response to any environmental change. Emotions dictate a person's actions. Irritation in a situation can develop into anger, and our verbal cues change, becoming insulting or rude. Likewise, when good news is received, feelings such as happiness are noticed. The development of negative sentiments is usually unlikely. Emotions are a product of evolutionary advantage and are responsible for generating environmentally appropriate responses that we can use for survival. Part of the ability to show emotions is the social skill of detecting the emotions of those around and responding. However, as situations become more nuanced and complex, a shift in emotions often takes place. The human tendency to influence internal emotions and those of other people is the product of an emotional regulation (ER) process [1].

The complex culmination of detecting emotional cues, generating appropriate responses, and emotional regulation is summarized as emotional intelligence (EI) [2,3]. The quality of emotional regulation depends on a person's emotional intelligence.

Emotional regulation takes place in the limbic system. Fear, anger, and happiness, which dictate our behavioral and emotional responses, are controlled in different sectors of the limbic system, namely, the amygdala, cingulate gyrus, and parahippocampal gyrus [4]. A 2009 study suggested a positive relationship between emotional intelligence and emotional processing in the prefrontal cortex and parts of the amygdala (fear recognition center of the limbic system). Lower EI levels contribute to high amounts of cortisol amidst stressful and anxiety-prone situations [5]. Raz S. *et al*. (2014) observed the neurological correlates of emotional intelligence preset for neurological behavior by employing a cumulative study of event-related potentials and a filled-out questionnaire with a physical performance task to map out and detect neurological pathways associated with the subject's response to event-related potentials and study the emotional responses developed as a result. The conclusions of the study revealed the extent to which neural areas, such as the occipital lobe, were used for viewing and generating emotional responses on the basis of visual stimulus points toward a greater degree of EI [6].

A 2023 systematic review on EI used neural pathway imaging to identify the neural correlates of EI. This review aimed to discern whether the neural correlates of EI depend on the same or different neural substrates [7]. A neural substrate is located in the central nervous system and underlies a behavior pattern or cognitive process. This review studies images from MR scans of the brain to determine the neural correlates associated with the response development of EI, which primarily consists of the ventromedial and ventrolateral cortex and anterior and posterior insula (thin tissue that separates the temporal lobe from the inferior parietal lobe). The ability of EI to detect emotions and formulate responses is correlated with the rostral (cranial) anterior cingulate cortex, a part of the nervous system that integrates emotion and cognition [7]. A series of recent studies claim that direct and indirect neural pathways in the central nervous system work together to regulate emotions that are perceived by a person and that the interconnectedness of specific nodes found in the neural pathways allows for the proper regulation of emotions [8] and could also possibly help connect the ER with the EI. The neurobiological function behind brain function in the development of emotion has attracted increasing attention in academic circles [9]. Studying/reviewing neural correlates that are involved in emotional regulation can provide a more profuse and in-depth understanding of the entire function of the limbic system, similarly providing a detailed connection between the neural pathways affecting both emotional regulation and emotional intelligence. This review focuses on neural pathways connecting the ER and EI.

2. Discussions

2.1 Biology Affecting ER & EI

2.1.1 Emotional Regulation

The limbic system provides the basis for all emotional regulation and processing aspects. The extensive process of emotional regulation involves the culmination of different regions of the limbic system in the central nervous system and neural circuits.

A review of research from 2005 shed light on the extent to which the amygdala plays a role in the emotional processing of mammals rather than just fear and pleasure. Thoroughly reviewing research models ranging from two decades prior, the amygdala has been known to hold great value in terms of emotional processing because it also plays a role in emotional learning and memory, the influence of emotion on attention and the perception of various situations, which can explain the variation in emotions from person to person in a situation [10]. Attention and emotion work as a result of neural circuits between the prefrontal cortex (PFC) and the amygdala. Together, the PFC and the amygdala guide the activities of emotional stimuli from a situation and attention processing. There is a direct relationship between an individual's emotional stimulus and the level of enhanced processing of the situation. The interconnection of emotion and attention processing occurs along two pathways depending on the situation in which the individual is in. One pathway includes a top-to-bottom hierarchy in which the PFC directly signals the amygdala with a subconscious accumulation of information from the environment in a setting. The second pathway involves more enhanced processing of an emotional stimulus and works from the bottom up, from subcortical units such as the amygdala to the PFC [11].

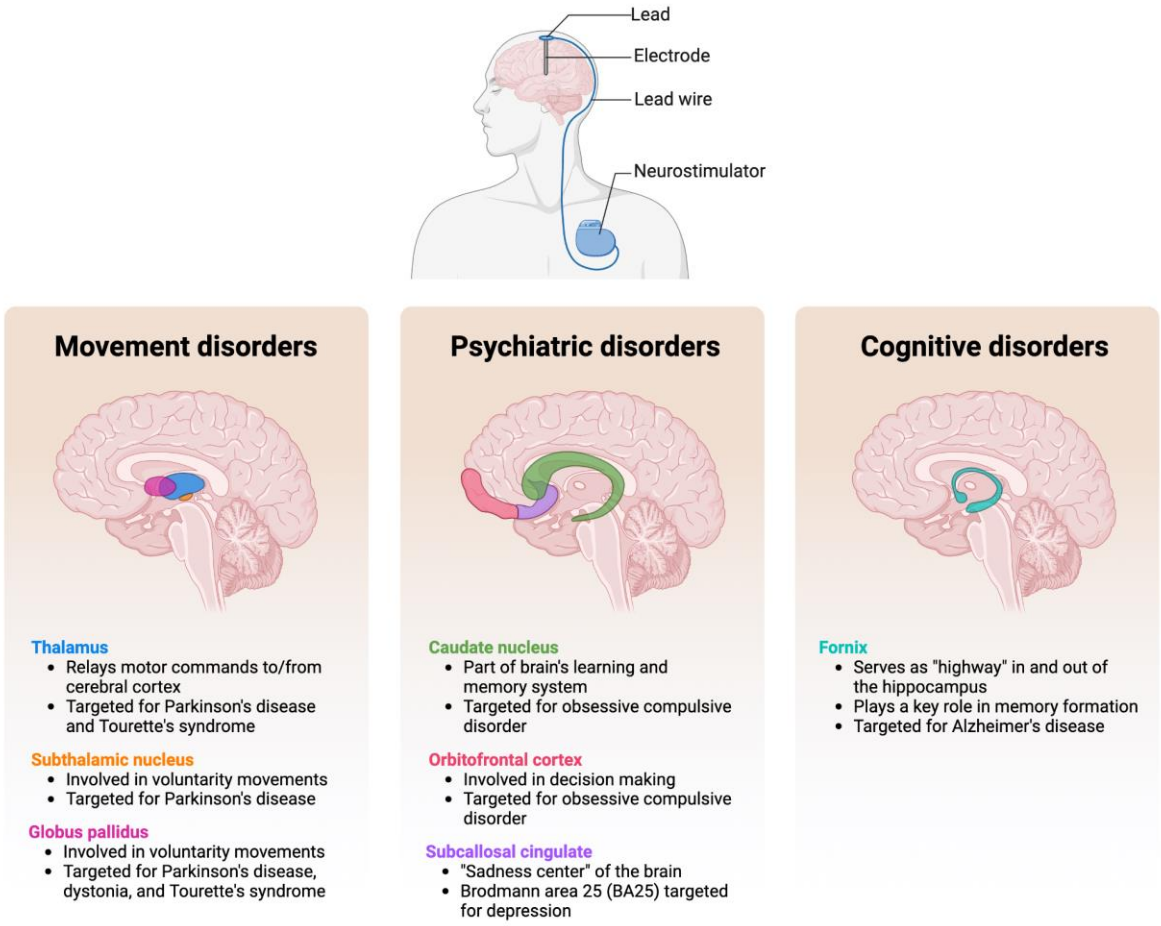

Figure 1. *Deep brain stimulation (DBS). Adapted from "Deep Brain Stimulation (DBS) Targets" by BioRender.com (2024). Retrieved from https://app.biorender.com/biorender-templates*

The bottom-up strategy allows for more attention devoted to a situation and leads to better emotion processing, enabling an individual's emotional regulation. A person better comprehends the emotional stimulus from a situation, which allows for better emotional regulation.

The PFC, the cingulate cortex that overlies the corpus callosum, and temporal cortices play important roles in emotional processing [12]. However, the exact regions of emotion representation are not noticed in scans of cortices in the limbic system because the prefrontal region is also the place where emotional processing occurs; thus, a 2006 research study outlined the intensity with which cortical regions were scanned with fMRI when an individual was shown a series of images to stimulate emotions [13]. Emotional valence reflects the extent to which an emotion is positive or negative. It is one of the primary layers of emotional perception. Emotional arousal refers to the strength of the emotional state. The twofold process of valence and arousal controls the processing of emotions in the prefrontal cortex and plays an important role in the ER. Emotional valence and emotional arousal interact with the emotional stimulus being picked up by an individual. The interaction between emotional stimulus and valence determines how well a person reacts in an emotional situation; it can also be used to determine the different types of reactions that people have to the same situation [14]. The depth of the emotional stimulus received from a situation dictates which parts of the limbic system are most activated. High-intensity situations involve the amygdala and PFC processing stimuli. On the other hand, minimal-intensity situations involved parts such as the insula and the angular cingulate cortex. The major emotional activity that takes place in the insula is the valence evaluation of primarily negative emotions and the processing of anxiety [15].

Growing evidence suggests that an individual's ability to regulate emotions is a cognitively demanding task. Employing strategies of emotional regulation and suppressing negative thoughts is often substituted by lower forms of mathematical or language comprehension. However, emotional regulation is employed much more by older adults than by young adults. This results in the conclusion that younger adults fail to allocate cognitive resources effectively when regulating emotions. Older adults show a greater affinity for dealing with emotions with increasing life experience and repeated practice in dealing with a surge of emotions. Younger adults employ emotional regulation at times of need only, and it is not a chronic reminder for them when they feel emotional stimuli [16]. Younger adults are more susceptible to some effects of cognitive decline in regard to emotional regulation, but the trend of emotional regulation becoming more resource-demanding decreases with age and repetition. Hence, younger adults find it harder to assess and quickly process positive and negative emotions than older adults do.

Emotional stimuli are assessed from a psychological and neurological perspective via a series of tests under the name emotional Stroop tasks. The primary goal of using these tests is to record the time it takes for an individual to procure an emotional reaction in a situation. Emotional Stroop effects (ESEs) are usually assessed to measure the valence of negative situations. Stroop tasks provide a significant amount of data for negative emotions because of the rapid response from the body. The high- and low-valence stimuli produce effective Stroop results because the immediate response is a result of evolutionary advantages. Negative emotions such as fear and anger prompt immediate responses because they signal a threat in the surroundings that the individual must act upon. A positive emotional stimulus does not produce major results unless the stimulus is from a life-essential object [17]. Hence, the ESE on emotional regulation provides different results depending on the valence of the emotional stimulus and the intensity of the emotions felt to generate an emotional response that can be measured.

2.2.2 Emotional Intelligence

Event-related potentials comprise brain responses from a specific sensory stimulus. Emotional intelligence is not merely cognitive-emotional processing; it involves the accumulation of emotional regulation, emotional processing, and changes in behavior when an individual is subjected to a change in emotional stimulus. Emotional processing and regulation are seen as subsections of emotional regulation. However, similar to emotional regulation, emotional intelligence is dependent on the neurophysiological health of a person. A 2013 study on the neural correlates of EI revealed that people who had suffered damage to their prefrontal cortex, right amygdala, and insular cortex reportedly presented lower levels of EI. Raz S. *et al.*, 2013 used visual stimulation to provide a connection between EI and ERPs. In conclusion, participants with higher EI performed or reacted more precisely to the visual stimulus than low-EI participants did [18]. This suggests a positive relationship between ERPs and emotional intelligence.

EI is linked together by neurocircuitry, which focuses on exactly which regions of the brain take part in determining the emotional intelligence of a person. The key functional regions involved in emotional processing under EI include the angular cingulate cortex, medial prefrontal cortex, insular cortex, and amygdala. The neural health of these brain regions significantly promotes better EI [19]. The neurodevelopment of EI includes not only neural regions but also neurotransmitters and hormones such as serotonin, dopamine, and oxytocin, which control emotional reactions. From a psychological perspective, EI’s major determinant is the production of a nuanced and situation-appropriate response by an individual and relies on factors such as the degree of empathy, judgment, and social perception; the prefrontal cortex is the key region responsible for high cognitive processing [20]. fMRI data from recent studies have shown that the prefrontal cortex is the main brain region involved in decision-making. Several recent studies have revealed increased blood flow to the prefrontal cortex in regard to making a decision in any situation through functional magnetic resonance imaging (fMRI) [21]. It is related to the emotional intelligence levels of individuals because the amount of activity in the prefrontal cortex is a precursor to suitable navigation and decision-making when in an emotionally stimulating situation [20]. This decision-making tendency in the prefrontal cortex is facilitated by a neural connection of the anterior cingulate cortex (ACC) with both the prefrontal cortex and the limbic system. The ACC was previously associated with only error detection, but increasing evidence from brain images and EEG scans has shown that the ACC is also involved in decision-making tasks, which include exploring alternatives and evaluating options when individuals are asked to make a decision. A neural link between the ACC and the insula facilitates the evaluation of negative stimuli produced by negative valence emotions. Owing to its connection to the limbic system, the ACC receives constant inputs from several regions of the system to synthesize information from behavioral cues to organize an emotional response [22]. Different parts of the ACC are activated by relatively simple emotions from emotional stimuli by the limbic system. The anterior cingulate cortex hence involves emotional processing, emotional learning, and regulation [23].

The hippocampus plays a primary role in memory revival rather than social emotion processing. The functioning of the hippocampus involves self-experienced memory and processing of emotional stimuli that are produced not only by an individual but also by individuals around a person. External emotions are often complex to process and respond to, which is why the hippocampus evokes personal memories as an information base to cultivate the appropriate emotional response. The hippocampus is usually involved in emotional processing for longer duration emotional experiences to register as much memory as possible and increase the information base. Hippocampal activity is rare in times of immediate and fast-paced situations. Hippocampal activity for different emotions also differs depending on the intensity of the emotional stimulus and is a more detailed and extensive process when a complex emotional stimulus is received [24].

From a social and psychological perspective, the cognitive abilities of people are dependent on emotional intelligence. Individuals with greater EI are more likely to cope with stress, deal with anxiety, and maintain a healthy mental atmosphere. Emotional intelligence levels vary for each person, but the use of emotional regulation methods can enhance emotional processing and help a person navigate social situations more quickly and more precisely. EI also contributes to proper brain health across the neural regions associated with emotional regulation and processing [25].

The increased cognitive ability that EI provides an individual can also be harnessed to identify health disorders. A 2007 study revealed that individuals with higher EI levels were less likely to become addicted to substances such as tobacco, cannabis, and other drugs than individuals with lower EI levels were. This decrease in addiction tendencies resulted mainly from a healthy decision-making environment between the prefrontal cortex and the limbic system. Similarly, people with higher EI are less likely to suffer from mental health disorders such as depression or anxiety because of the emotional regulation that occurs through neural networks when emotional stimuli are received [26].

2.2 Emotion and Cognition

Emotional stimulation is a frequent aspect of an individual’s daily life even though it occurs through different means and media. Upon receiving emotional stimuli, emotional processing capacities vary from person to person, affecting a person's overall cognitive health to varying degrees. Emotion and cognition create a twofold system, and both are equally dependent on the functioning of the other. A mistake in the processing of certain emotions can potentially reduce memory and cognitive functioning. According to a 2006 study, emotions can have a positive or negative impact on cognition depending on the accuracy of processing emotions [27].

Cognition and emotions are linked by an extensively intricate system. Cognitive abilities are regulated in the limbic system, mainly in the prefrontal cortex. On the other hand, a recent series of studies revealed the effects of emotional sensations not only via neural processing but also in other organs of the body. Organs in the body are found to emit signals processed by emotional neural regions as emotional stimuli. Emotional processing also occurs from internal stimuli and is not just centric in receiving external stimuli from an individual's surroundings. Neural images from recent studies have shown an overlap in emotional signals that undergo interception in the body. Evidence from a multitude of studies has highlighted the importance of introspective awareness (IA) in navigating various social-emotional settings. IA allows for congruence between empathy and self-awareness, which improves emotional processing and allows for better emotional connection in an emotional setting [28].

Emotional priming provides evidence for the unconscious perception of emotion. Emotional priming denotes how unconscious perception influences behavior [29]. Emotional processing and cognitive control occur hand-in-hand. Most of the body's cognitive control occurs through the resolution of conflict. Emotional stimuli drive cognitive conflict control, which contributes to cognitive processing and results in an appropriate response [30]. Cognitive priming has been shown to improve the working memory of young individuals and enhance recognition of their surroundings, which is necessary for generating the appropriate emotional response [31]. Emotional priming can subconsciously affect how an individual perceives and responds to information. Emotional priming affects not only cognitive control for conflict resolution but also the level to which an individual experiences emotional priming, which can affect his/her perspectives of viewing things. Additionally, which emotion is being primed is a pivotal aspect of changes in cognitive processing and behavior. Positive valence emotions allow for more optimistic tendencies of behavior, whereas negative valence emotions cause a person to respond carefully. Negative valence emotions also cause a person to develop a more analytical approach to emotional stimuli [32].

Emotion affects cognition in the sense of memory, problem-solving, and responding in the right way to an emotional incident. A heterogeneous mix of emotions can be inferred from the level of EI and emotional stimulus involved, e.g., colors, phrases, or certain sounds. The emotional stimulus process is distributed across a dense neural pathway, which can allow an individual to discern mixed emotions via different cognitive techniques [33]. Overall, the reception of emotional stimuli and their cognitive processing have a profound impact on the development of emotional recognition techniques and emotional regulation in social and individual circumstances.

2.3 Survey Review

Emotions are involved in almost every situation of an individual's life. As an evolutionary advantage, emotions have helped humans survive, develop communicative skills, and connect as a community [34]. A higher degree of awareness in humans is often credited to their range of emotions. Emotions integrate numerous aspects of our brain in computing a proper response, and the ability of the human mind to process heterogeneous emotional stimuli leads to nuance and intricacy in an individual's life. Neural networks across the limbic system and processes involving emotional stimuli, perspectives, and cognitive responses produce a powerful dynamic with a constant input of thoughts, varying changes or stimulating factors in the environment, and actions [35].

The pursuit of research from the perspectives of psychology and neuroscience with respect to emotional processing is a significant topic in the scientific community. However, the findings revolving around proper emotional regulation, the generation of appropriate responses to emotional stimuli, and coping with negative valence emotions have to reach the correct audience at the correct time. Older adults (above 25 years) often show greater affinity for emotional regulation and emotional processing. Younger adults (14--25 years) found emotional regulation to be more cognitively resource-demanding [16]. However, it may be true that resource partitioning, while emotional processing becomes less strenuous with age and repetition, making an increasing number of younger adults aware of information surrounding correct emotional processing, would cultivate an emotionally aware community and smooth the dynamic between cognition and emotional processing from an earlier age.

2.3.1 Information collection

The least time-consuming yet promising approach to understanding the extent to which adolescents are familiar with the concepts of ER and EI was through a virtually shared Google Form questionnaire. The survey was set on a slightly informal note and was completely voluntary. The targeted audience for the survey was teenagers aged 13--18 years. However, a compilation of 64 responses across a span of 3 weeks included responses from a participant pool of ages 14--22. The majority of the participants were 16 years old. Most of the volunteers were either in their junior year or senior year of high school. According to the questionnaire statistics, 73% of the volunteers were female, and 27% were male. The questionnaire was designed to not delve too deep with respect to personal information and merely resorted to asking the participants their ages and school grades.

The survey was designed purely with the aim of trying to understand the extent to which high school students were familiar with emotional regulation and the concept of emotional intelligence. The survey also asked the participants how they coped with primarily negatively valenced emotions and asked them where they learned about ER and, in particular, the importance of mental health. The survey also asked them to provide input on which medium would be the most effective in terms of spreading mental health and emotional regulation awareness. Among the 64 participants, 87% agreed that they had been overwhelmed by emotions. They were familiar with emotions, leading to them burning out, overthinking, and hence being ‘cognitively demanding’.

2.3.2 Results for ER

On an occasional basis, the participants were familiar primarily with the term emotional regulation. A majority of the participants were accustomed to certain aspects of emotional regulation. They understood the idea and the general aspect of emotional regulation but were not as well versed with respect to ER strategies or how to carry out ER techniques to initiate emotional control exactly. When asked to self-evaluate themselves on a 1--5 scale on their ability to recognize their emotions, most of them responded by giving themselves a score of 4. This suggests that most of the participants were not completely unaware of the role of emotions in our daily lives and that identifying the correct emotions at appropriate times allows for the generation of the correct response.

The participants were asked about the personal techniques that they found effective in managing emotions whenever they felt overwhelmed by them. The answer choices provided different commonly used techniques that fall under the umbrella of the ER strategy of mindfulness-based interventions. Their responses proved that even though the participants were not fully aware of mindfulness-based interventions, they were already practicing a certain aspect of them.

The survey included small and succinct definitions of ER and its strategies, which included mindfulness-based interventions, cognitive reappraisal, emotional acceptance, and emotional validation. These definitions were used for participants to become more aware of and obtain a general idea of different types of ER strategies. The definitions also served to equip participants to answer the following questions on which strategy they thought would best help them regulate negative valence emotions. The survey focused solely on negative valence emotions such as grief, fear, anger, and aggression because it was much easier for participants to relate to being overwhelmed by them and simpler for them to identify which ER tendency they could use when experiencing an influx of negative valence emotions. For emotions such as anger, frustration, and aggression, the majority of the participants decided that they would use mindfulness-based interventions, emotional acceptance, and cognitive reappraisal. When asked about emotions such as grief, sadness, and fear, most of the participants decided to use mindfulness-based interventions, emotional acceptance, and emotional validation.

The most commonly chosen technique is mindfulness-based interventions, which can work to regulate negative emotions by inducing positive behavior or emotions or providing positive stimuli. The most commonly chosen way to practice mindfulness-based intervention was by listening to music and writing down thoughts or journaling and engaging in some form of physical activity.

A study from 2019 noted the increasing dependence of young adults on music and investigated whether listening to more positively stimulating music indeed regulates mood and emotions. Their findings suggested that listening to music helps with ER via two different methods of mindfulness-based interventions, where people, especially young adults, use music to shift their negative mood to a positive emotion. Listening to classical music can help in times of aggression and frustration. Happy and uplifting music can help individuals overcome sadness and grief. Sometimes music can help validate emotions and help people find the genuine reason for feeling the reason they are [36]. However, emotional validation can amplify certain emotions, so most people listen to music to intervene in the processing of negative emotions. A 2017 study reported that engaging in physical activity stimulated less anxiety and decreased the intensity of an individual's response to negative stimuli and emotions [37].

2.3.3 Results on EI

When the participants were asked if they were familiar with the term emotional intelligence, 50% of the participants were completely familiar, and 41% of the participants had heard this term occasionally. More participants were familiar with EI than with ER. From the assessment of further question responses, it was significant that the survey volunteers were better versed with respect to EI in that the majority of the participants were already familiar with EI being not a definitive quantity and that people do have the ability to become more emotionally intelligent with age, which is also closely associated with the detail to which a person processes their emotions and can detect the emotional stimulus provided by other people as well. Eighty-eight percent of the participants also stated that there is a connection between emotional intelligence and emotional regulation. On this basis, we concluded that younger adults were familiar with EI rather than a subsection of emotional regulation.

2.4 Emotional Limbic System

The emotional limbic system consists of several organs that often have different and overlapping functions in terms of reacting to or generating an emotional response. The processing of emotional stimuli is a highly nuanced process involving steps such as sensation, perception, and understanding, ultimately eliciting an emotional response. Emotional processing is guided by the culmination of several different functions that take place via organs of the limbic system [38]. To respond to an emotional response, the emotional stimulus must first be picked up from the environment. The amygdala is responsible for picking up emotional stimuli from the surroundings. The amygdala also engages in 'emotional hijack' situations wherein the emergency emotional stimulus is picked up and processed by other limbic organs while being controlled by the amygdala in the form of a downup hierarchy [39]. The primary motivator for the hijack of the amygdala is negative valence emotions such as fear or stress [40]. The perception of emotions acts as a stepping stone for the understanding of emotions. The hippocampus (anterior) is involved in the cognitive functions of perception and is involved in the recall of past events [41]. The role of the hippocampus in memory recall is significant for the perception of emotional events on the basis of prior experiences [42]. Emotional perception in the hippocampus is used to generate an appropriate emotional response to an emotional stimulus that is picked up by the amygdala [43][38]. The hippocampus also supports the navigation of spatial memory, which promotes the inhibition of impulse response tendencies to emotional stimuli, which is the result of 'amygdala hijack'[38]. Emotional moderation takes place in the insula. The anterior insular cortex (AIC) functions to allow an individual to move away from negative valence emotions stimulated from emotional stimuli. The insula acts as a hub for neural and sensory inputs that intervene in emotional moderation to inhibit depressive or negative valence emotions [44]. Comprehension and understanding of emotional stimuli occur in the PFC. The PFC observed in mice across various experiments via microfluidics effectively highlights the processing of emotional stimuli and emotional recognition [45]. The central area for critical thinking that can be applied to emotional comprehension takes place in the dorsolateral PFC [38]. In terms of emotional regulation, the ventromedial PFC is important for emotional processing [38]. The final step of emotional processing involves eliciting an emotional response. The anterior cingulate cortex (ACC) is a system that is mostly goal oriented and directed. This system is largely based on reward and motivation and depends on how a person thinks and acts [19] [38]. The final step of emotional utilization and behavior is complete after passing from one organ to another to undergo thorough emotional processing. This detailed emotional processing allows an individual to produce a reaction properly aligned with the emotional stimulus that was initially picked up.

Table 1. *Organs of the limbic system involved in emotional processing and emotional regulation*

Reference	Brain Region/Network	Function in Emotion Regulation	Role in Emotional Intelligence	Associated EI Component
[46] [39] [2]	Amygdala	The amygdala is a control center for negative emotions. The amygdala is a vital region for the generation and expression of primarily negative emotions. The amygdala takes in external stimuli and allows the individual to react to that emotional stimulus.	The primary role of the amygdala in EI is to store memories and memory association with various objects or other individuals.	In the case of EI, the amygdala is associated with reviewing emotional significance. The amygdala is responsible for detecting emotional stimuli and reviewing which external information is important in terms of developing an emotional response and processing the memory of that experience for future reference as well.
[42] [47]	Hippocampus	The hippocampus plays an important role in the cognition of social, and emotional events and emotional processing. For emotional processing, the hippocampus aids in spatial memory navigation and includes the processing of autobiographic memories.	The hippocampus is involved in the creation of episodic and periodic memory. This creation of long-term memory is presumably enhanced for people with higher EI to use for sensory cues and emotional content. The potentially amplified recall tendency of people with higher EI enhances the ability to generate a response to social and emotional situations.	The hippocampus is largely associated with reflecting to pick up sensory and emotional cues from past or episodic events which pose as an indicator of emotional intelligence. The hippocampus sends information inputs to the amygdala which are used to generate the proper emotional response.
[44] [48] [49]	Insula	The insula preserves the connections between past experiences and emotional responses. It is a hub for emotional, neural, and cognitive sensory inputs and passes sensory outputs through dense neural networks to different subcortical regions of the limbic system.	Interoception and perception are major functions of the insula in terms of emotional intelligence. The insular cortex or insula is associated with stress and anxiety relief. A large role of the insula is to identify and react to sensory stimuli in the environment.	An essential part of emotional intelligence is the correct processing of an individual's emotions and generating the correct response to an emotional situation by evaluating the emotional stimulus being picked up or another person's emotions. Since the insula picks up sensory stimuli, people with a higher emotional intelligence quotient respond better in terms of emotional

				processing and response generation with incoming sensory-emotional stimuli.
[45] [50] [51]	Prefrontal Cortex (PFC)	Responsible for emotional formation, generation, and regulation. The orbitofrontal cortex is responsible for the processing of emotional stimuli and the recognition of emotions.	A research study in 2011 determined that people with high EI showed better emotional processing in the PFC. The neural basis of perception and EI correlates with the role of PFC in emotional processing.	The PFC is cumulatively associated with the processing of emotional stimulus and emotional recognition. The PFC is mainly associated with the functions of interpretation, expression of stimulus, and regulation. The medial frontal cortex allows for the organization of responses to emotional stimuli and regulations of emotions.
[52] [53] [23] [19]	Anterior Cingulate Cortex (ACC)	The anterior cingulate cortex (ACC) plays a role in emotional regulation in terms of eliciting emotional responses to stimuli picked up by the amygdala. The ACC is associated with reward input and reward-related information processing.	The anterior cingulate cortex in emotional intelligence is responsible for emotional awareness and the conscious experience of emotions. The anterior cingulate cortex accelerates the processing of goal-related stimuli for establishing emotional responses.	The main purpose of the anterior cingulate cortex is autobiographical or self-thinking. As seen before this approach is largely guided by the primary function of the ACC of goal-oriented and related behavior.

2.5 Large-Scale Neural Networks Involved in the ER

Functions in the limbic system, from emotional perception, comprehension, regulation, and response, occur via connections over vast neural networks [54]. The regulation of emotions is a multiple-phase process that requires the involvement of several areas and organs of the limbic system. These neural networks aid in improving the efficiency of emotional processing [55]. The existence of neural networks allows the brain to initiate valence emotional responses to stimuli that are picked up externally or through any internal processing of emotions [56]. Some primary neural networks are involved in the emotional processing of attention, motivation, work alignment, and memory-induced stimuli. The ventral attention network (VAN) is a sophisticated network that collects vital information. The VAN draws an individual's attention to important new information that is presented in the environment [57]. The VAN works in tandem with the dorsal attention network (DAN). The dorsal attention network guides the brain to detect more intricate information, such as geographical locations, landmarks, and intricate details, while the VAN highlights any unexpected, urgent information [58]. The VAN is located in the right hemisphere and spans the ventral PFC and parietal lobe [59]. With respect to emotional regulation, the VAN has been observed to pick up several forms of emotional stimuli but is not in charge of the emotional processing of that stimulus. Recent studies have shown that an individual's tendency to avoid negative valence emotions suggests the involvement of the VAN in mediating emotional stimuli that are picked up [60]. Once the VAN picks up an urgent stimulus, the autonomic interoceptive network (AIN) allows an individual to regulate their energy and emotional state. This network allows the body to adapt to its surroundings with the influx of emotional stimuli and maintain homeostasis. Interoception and perception are important parts of AIN, and interoception plays a pivotal role in emotional regulation by allowing the body to adjust to its surrounding atmosphere. Interoception allows the body to conduct itself to conserve energy and adjust to any changes in the surroundings [61]. The accuracy of introspection is dependent on the complexity of the environment. Introception is considered a primary ER strategy for effectively processing and regulating emotions. Introception works in tandem with other emotional regulation strategies, such as reappraisal and distraction. The level of interoceptive accuracy determines how well a person can regulate emotions and procure an emotionally appropriate reaction [62]. The frontoparietal control network (FPN) mostly controls executive skills such as memory processing and attention and elicits goal-oriented behavior. This network ensures that an individual can avoid being influenced by any interfering stimuli from the environment. The formulation of action plans using only necessary environmental stimuli occurs in the frontoparietal network [63]. The FPN plays a critical role in the navigation of several mental health disorders, such as anxiety, depression, and schizophrenia, in terms of emotional regulation. Connections in this network allow an individual to process emotional stimuli in a goal-aligned manner. Different connectivity patterns in the FPN reduce an individual's ability to process mental health stimuli. A 2018 study concluded that depression symptoms were inversely proportional to FPN connectivity and that decreased connectivity across the frontoparietal network led to increased depression symptoms in individuals. Owing to its goal-related processing, this network plays a large role in mental health regulation and cognitive control [64]. The anterior insula, ACC, and ventral striatum are part of the salience network (SN). The SN not only processes reward-oriented stimuli but also provides a means for distinguishing between internal and external stimuli. Like the VAN, the SN allows an individual to pay attention to only relevant stimuli. The salience network plays a vital role in vigilance patterns and arousal tendencies in individuals. The primary hub for emotional processing in the SN is the anterior insula, and dysregulation in the insular cortex has been associated with perception dysregulation and elevated stress levels, promoting anxiety and depression tendencies [65]. Increased connectivity among insular nodes in the salience network helps an individual determine emotionally relevant stimuli from the overall stimulus being picked up from the environment and process any reward-related opportunities or unfold any emotional valence information from the stimulus that is determined to be relevant [66]. The default mode network (DMN) is solely activated for self-reflection and introspection [67]. This network is active even in the body's resting state. The default mode network consists of the anterior medial PFC, anterior gyrus, and posterior cingulate cortex (PCC) [68]. This network works primarily for self-intrinsic thought, daydreaming, and thinking about past events or prospects [69]. Greater activation is found across this network with the onset of puberty, and a result of this greater activation is social phobia [70]. A study with social anxiety patients revealed an increase in the PCC region and overall default mode connectivity [71]. The DMN also delves into the roles of social-perspective reflection and episodic memory when thinking about past events and the evaluation of surprise events that individuals experience throughout their daily lives [72].

Table 2. *Neural networks in charge of processing emotions and navigating the emotional response of an individual*

Reference	Neural Network	Primary Function	Emotional Process Contribution & Clinical Relevance
[59] [57]	Ventral Attention Network	This attention network works when the body is resting, VAN ensures cognitive control of the body remains active. The frontal and parietal cortices have been known to be involved in spatial attention. This network is employed for carrying out tasks that require attention. Increased activation and performance in this neural network leads to an increased ability of an individual in value and attentional stimulus-based decision making, processing of rewards, and avoiding negative emotional stimulus.	This network draws the body's attention toward relevant stimuli in the environment and asserts control over spatial attention while regulating motor responses of the body according to the attentional stimulus. For emotional regulation, attention-based stimulus can allow an individual to judge a situation and generate an appropriate emotional response.
[61] [62]	Autonomic-Interoceptive Network	Introception and the autonomic nervous network play a role in helping the body adapt to its ambient environment. This network helps keep the body in homeostasis while allowing an individual to adapt to any changes in their environment.	This network adheres to helping the body adapt to its surroundings and changes in the environment. This network allows a reaction to be formed depending on contextual analysis of the surrounding environment as well. The autonomic-introceptive network causes a shift in ER strategies over time too, causing an individual to change or determine which ER strategy to use depending on the situation.
[63] [73] [74]	Frontoparietal Control Network (FPCN)	The frontoparietal network is associated with concentration and executive control. Some cognitive abilities that are guided by this network are active working memory, disregarding unnecessary stimuli, and using relevant, important stimuli to formulate action plans or strategize to reach a certain goal. This network is used greatly for task-specific functions, their main function revolves around processing relevant stimuli being picked up from the surroundings to guide goal-related behavior.	Neuroimaging findings from previous research concluded that the frontoparietal network plays a vital role in emotional processing. The primary ER strategy used to regulate emotions in the frontoparietal control network is cognitive reappraisal. The emotional regulation strategy of this network works mostly to suppress emotions rather than to actively process them and generate an appropriate reaction according to the emotional situation. The main function of this network is to synthesize task-relevant stimulus and create a goal-oriented plan which is

			generally associated with a reward.
[65] [75]	Salience Network	The primary function of this salience network is the perception of feelings driven by a reward. Much like the insular cortex, the salience network is associated with reward-related behavior. In the limbic system, the SN promotes greater control and alertness. The SN acts as a mediary between the default mode network which processes task-irrelevant behavior and the frontoparietal network which processes task-relevant behavior.	The integration of the ACC and the anterior insula plays a critical role in evaluating the importance and relevance of internal and environmental stimuli that guide the behavior of a person. Research evidence has shown that high salience stimulus leads to increasing feelings of stress and anxiety. For clinical relevance, in the case of drug dependence, high salience stimulus can increase the probability of drug relapse or addiction. Neural imaging evidence denoted that in individuals who suffered from PTSD, there was increased hyperactivity in the anterior insula and the anterior cingulate cortex.
[67] [76]	Default Mode Network	This network is activated in times of self-perception or autobiographical thought. The default mode network is one of the three main neural networks and includes the anterior medial prefrontal cortex, posterior cingulate cortex, and angular gyrus. Memory processing is another task of the DMN, memory processing usually occurs as a reviewing of memories or processing of nostalgic feelings.	This network undergoes functional changes due to fluctuations in sleep patterns in an individual. Insomnia or the inability to sleep causes an imbalance in DMN. The inability to sleep increases activity in the PFC but reduces or inhibits function in the posterior cingulate cortex. This disrupts the functioning of the resting state activity of the body and leads to poor functioning of the DMN.

2.6 Integration of emotion, cognition and neuroplasticity

Neuroplasticity enables stimulus-oriented changes in the nervous system. Neuroplasticity in the brain occurs due to changes or modifications in neural networks and changes in function and structure. Over time, neurons change and modify themselves to increase their strength and efficiency, reflecting synaptic plasticity, which makes neuroplasticity a critical phenomenon that allows individuals to adapt to the environment [77]. Research from 2016 revealed that a change in the environment stimulated the brain to undergo cognitive enhancement, thus improving its efficiency in the future. Enhanced cognitive function decreases its decline in the future and promotes better brain health [78]. The repeated and consistent use of ER techniques to process emotional stimuli has resulted in distinct patterns and networks of response and changes in behavior in social settings. Research over the years has concluded that the functioning of these patterns is highly automatic, which suggests that repeated emotional processing plays a part in conditioning or influencing brain regions present in neural networks related to emotional regulation and processing. In the anterior insular region of the brain, the ER technique of emotional suppression is primarily evident. Emotional suppression is a vital part of adaptation and social behavior [79]. A myriad of emotional stimulus inputs from social situations prompts the use of emotional suppression [80]. The insula acts as a central hub for salience stimulus processing and a variety of sensational stimuli, such as taste, smell, and sight, and the insular cortex is largely associated with emotional suppression. A neuroimaging study from 2011 revealed the close relationship between repeated emotional suppression in the anterior insula and an increase in the volume of the insula. The positive relationship between insular volume and usage was depicted only by emotional suppression and not by any other ER strategy, such as cognitive reappraisal. Projected insular growth occurred in both the left insula and right insula. This conclusion regarding the growth of the anterior insula with consistent use of emotional suppression supports the increased efficiency of an individual's emotional awareness of a social situation [79].

In addition to promoting neuroplasticity, which is a more efficient process of carrying out brain functions, it also promotes the healing of injured cranial regions [77]. The recovery processes of neuroplasticity range from adaptive changes at both the structural and functional levels. Changes in brain function as a result of neuroplasticity occur from molecular changes to alterations as a form of recovery across neural networks [81]. The central nervous system inherently provides some functional intervention after traumatic brain injury. However, these interventions are insufficient for long-term recovery of a cranial region, and recent research has concluded that environmental diversity or enrichment has a unique effect on neuroplasticity. Environmental diversity promotes an influx of new experiences that demonstrate better cognitive functioning, enhance neuroplasticity, and affect emotion, attention, and memory in an individual. Experience has been shown to promote better remodeling of the brain after injury [82]. A change in the environment provides enhanced stimuli, which promote increased stimulation of sensory, motor, and cognitive levels [83]. Under a negative environmental stimulus, brain remodeling or recovery can be impaired. Negative environmental stimuli, such as stress, low physical stimuli, or extremely high physical stimuli, promote extremely high levels of fatigue in the body. High levels of fatigue can potentially impair the central nervous system, especially the hippocampus. Impairment in the hippocampus is associated with neurodegenerative diseases such as depression and, in some cases, has negatively altered neuroplasticity mechanisms [84].

2.7 Methods for ER

A psychology study from 1994 defined the process of ER as an extrinsic as well as intrinsic process, meaning that the internal regulation of emotions in our body often reciprocates with external results. Harmful effects on the body may prevail amid unhealthy emotions that may be built up internally. The two main steps toward emotional regulation are the frequency with which ER is carried out and the success of ER in generating a situation-appropriate response. ER strategies such as mindfulness, cognitive reappraisal, acceptance, and validation of emotions and the frequency with which individuals use them in their daily lives point to varying levels of emotional awareness and regulation [85].

2.7.1 Mindfulness-based interventions

Mindfulness provides awareness that comes from nonjudgmental observation by a person from their surroundings. Mindfulness-based interactions focus on using meditation and positive emotion-based interventions to develop emotional regulation tactics. Mindfulness intervention allows a person to self-regulate emotions to harness positive behavior, emotions, and cognition [86]. The ability to self-regulate emotions through mindfulness interventions helps a person avoid behavior change and react negatively to self-regulation setbacks. Mindfulness allows the recovery of emotions through the dual effects of curiosity and nonjudgment [87]. Nonjudgment prompts a person to embrace nonreactivity. It cultivates a thought process without any bias or one-sided thoughts and that keeps any additional emotions that might arise suppressed.

2.7.2 Cognitive reappraisal

Cognitive reappraisal can change a person's outlook on an emotional situation. Cognitive reappraisal is an important aspect of emotional regulation. Cognitive reappraisal involves neurological correlates in the ventrolateral and prefrontal cortex of the nervous system. Success in cognitive reappraisal can be detected by activity in the prefrontal cortex [88]. A simple aspect of cognitive reappraisal is to view a situation differently. Instead of focusing on the wave of negative emotions being experienced, this technique allows a person to judge whether his emotions are warranted depending on the entire background of the situation. People who practice reappraisal strategies in actual life avoid showing a full-out display of emotions, which could lead to more negative circumstances in the future. They also have positive extrinsic physiological effects, such as low blood pressure in stressful situations and good cardiovascular health in the long run [89]. Cognitive reappraisal engages the thought and decision-making parts of the central nervous system (prefrontal cortex) to navigate each situation, look at all the perspectives and generate the appropriate response. Over time, the practice of cognitive reappraisal has significantly decreased in people who feel negative emotions immediately in the face of adversity; a 1990s laboratory study concluded this [90].

2.7.3 Emotional acceptance and validation

A breakthrough in determining acceptance as a strategy of emotional regulation occurred in 1990. A series of experiments demonstrated that emotional acceptance reduces stress, anxiety, and depression. Emotional acceptance does not work as a form of cognitive reappraisal [91]. The acceptance strategy of emotions involves a more therapeutic approach rather than a neurological viewpoint. The basis behind acceptance is seeking clarity by perceiving and understanding every emotion a person is feeling. Most acceptance strategies fail due to a lack of clarity in perceiving emotions. Emotional acceptance allows for a rational reaction in emotional situations.

The validation of emotions is closely related to the suppression of negative emotions such as sadness, anger, and frustration. An increased quantity of negative emotions makes it difficult to look past them and suppress them to regulate emotional activity in the brain. Emotional validation allows a person to justify and elucidate why and how he/she is feeling this way and reduces the potential magnitude of emotions that might occur when a person is confronted with an emotional situation. Recent studies have shown that validation techniques work differently for different emotions. The validation of emotions such as sadness and fear enhanced positive emotions such as happiness and confidence. However, validation for feelings such as anger might cause an increase in negative emotions as people try to justify the feeling of anger [92]. In such cases, invalidation works better for emotional regulation. Therefore, the balance of validation and emotional invalidation work together for emotional regulation.

3. Conclusion

3.1 Survey Conclusion and Educational Application

The circulated survey results showed that it is not uncommon to be overwhelmed by emotions, and even if it does not start after a certain age, we feel a larger and much stronger influx of emotions as we go through adolescence. Today, for good reasons, many teenagers and young adults are somewhat aware of the growing importance of mental health and are aware that mental health is a contributing aspect to living healthily in all aspects. When the survey was circulated, the main medium through which the participants became aware of mental health and emotional importance was social media. Social media platforms contribute to providing knowledge about mental health and are a widespread medium for gaining awareness of its importance. When asked what would also be a preferred medium to learn more or gain the opportunity to learn more about dealing with and coping with emotions, most participants replied that schools and education centers should actively promote mental wellness and make an increasing number of students aware of its importance from an early age. Being familiar with ER strategies and techniques to manage emotions from an early age will make the cognitive processing of emotions and emotional stimuli much less resource-demanding. A recent study in 2023 revealed that adolescence is a vital period in which individuals learn effective ER techniques due to increased stressors (emotional stimulus promoters), such as increased academic stress, examination stress, and increased relationships. Providing an environment in which they are able to analyze their emotions properly such that they are feeling and using ER strategies can reduce the chances of emotional dysregulation for teenagers in the future and lead to a more nurturing environment for students to develop emotional intelligence. Emotional regulation can enhance a student's engagement in school activities and enhance the relationships of the student as well. Being able to identify the cognitive challenges of students with respect to emotional processing can help them target specific school programs and interventions [93].

3.2 Emotional Regulation Interventions

Regardless of whether they are interventions for mindfulness or emotional validation, emotional regulation is a complex and multifaceted task. Interventions also include constant monitoring of changes in emotions when emotional regulation occurs. Different motivating factors to monitor emotional regulation call for different strategies to observe changes—sometimes mere questionnaire inventory and sometimes instruments or electronic tools and machines. Digital technologies and tools have contributed substantially to many recent breakthroughs. The increase in social media technologies. Apps on smartphones and watches allowed for an increased surge in mental awareness and emotional regulation. This positive influence of social media on mental health regulation is a fairly important and recent advancement. Similarly, advancements in tests related to negative emotion regulation, such as the Ecological Momentary Assessment (EMA), have made experience sampling much easier and convenient for capturing negative emotions to use emotional regulation strategies to achieve more positive attitudes among patients. Just-in-time adaptive interventions (JITAIs) are specifically designed for emotional regulation. The emotional regulation interventions provided by the JITAI have been used for providing 'just-in-time' interventions in mental health cases such as suicide attempts, alcohol abuse, and drug abuse cases. Another promising intervention technique is virtual reality, which aims to address emotional dysregulation and anxiety disorders such as PTSD [94]. The inclusion of virtual reality can allow people to practice self-regulation by potentially practising to ignore anxiety and stress triggers to avoid being overwhelmed by a surge of negative emotions.

3.3 Advanced Analytical Approaches in ER Research

Research on emotional regulation is an up-and-coming area of investigation. Major interest in this topic did not emerge until the early 1990s. The initial advent of ER research prompted scientists to study ER techniques and their effects and implications using their existing lab equipment. However, the methodical approaches to studying emotional regulation have largely been nuanced to encapsulate the multifaceted process involving both internal and external inputs [95]. ER research analysis has shown tremendous growth in terms of analysis and assessment with the use of several technological advancements. Given that emotions guide an individual's behavior in response to any environmental stimulus, goal-directed or emotionally guided behavior is an essential aspect of analyzing emotional regulation. Currently, only a few resources are available to predict the process by which ER strategies influence goal-oriented behavior, but using methods such as sequence-based performance tasks and behavioral cues can help in assessing ER techniques [96]. Some major initial advances in ER research have occurred by neuroimaging techniques [97]. Functional magnetic resonance imaging (fMRI) is a widely used method to visualize emotional regulation processes in various regions, such as the amygdala, PFC, insula, and many other limbic system regions. Many studies have focused on capturing the workings of emotional processing for ER across neural networks. Electroencephalography (EEG) is used when fMRI is generally not viable. EEG provides a more in-depth understanding of connectivity patterns between ER-based neural networks. The use of EEGs has paved the way for the distinction of ER strategies such as distraction and reappraisal and is beginning to provide insight into how emotional stimuli are processed, which is depictive of how ER strategies work [96][97]. Conducting psychophysiological analysis to study ER provides a multifaceted approach to detect the effects of emotional regulation. Psychophysiological research has focused primarily on the autonomic nervous system (ANS), which interacts with several other life systems, such as the endocrine system and the immune system. Owing to these interactions, the side effects of emotional behavior can be captured in different parts of the body, such as heart beat rate changes, pupil dilation, muscle activity in the face, and skin changes (color). This connection between peripheral side effects and CNS function can be used to understand the effects of emotional processing [96].

Over the past decade, several other additional technological advancements and assessment measures have been taken to encapsulate ER assessment and create simulations to allow researchers to control ER usage in daily and more commonplace situations. Ecological moment assessment (EMA) is a guided process that allows researchers to observe individuals to gather detailed information on ER practices, as it is employed in daily life. An EMA is a two-way process by which individuals feed data about the emotions they experience via smartphones or other digital aids. The use of more advanced biological sensors is a more accurate way of understanding the ER. These sensors detect behavioral and physiological mechanisms consistent with those of the ER. Biofeedback research involving sensors and even virtual reality (VR) is highly regarded as the most noninvasive and accurate method of recording physiological responses concerning inputs provided by emotional regulation inputs. Biofeedback will not only help in ER research but also improve therapy intervention techniques for ER [98].

With recent advancements in the fields of applied biosensors and medical technology, such as capacitive micromachined ultrasonic transducers (CMUTs) and other transducers, the ability to monitor and observe neural pathways will become more relevant as technology advances with computing capabilities [99]. Furthermore, advancing capabilities in spatial sequencing technology will open doors to additional analysis capabilities to understand the neural pathways and correlations between emotional regulation, intelligence and cognitive mindfulness combined with cutting edge diagnostic and therapeutic technology [100] [101] [102 [103].

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AP, SV, KD: conceptualization, resources, formal analysis, writing – original draft, writing – review & editing.

Conflicts of interest

The authors declare that they have no competing financial interests or conflicts of interest.

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