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The interaction between cognition and emotion

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Cognition and emotion have long been thought of as independent systems. However, recent research in the cognitive and neurobiological sciences has shown that the relationship between cognition and emotion is more interdependent than separate. Based on evidence from behavioral and neuroscientific research, researchers have realized that it is necessary to propose a new conceptual framework to describe the relationship between cognition and emotion. In this article, recent research from behavioral, neuroscientific and developmental research on the interaction between cognition and emotion is summarized, and how the interaction of cognition and emotion might affect computer science and artificial intelligence is discussed. It especially focuses on the implications for affective computing.

emotion, cognition, interaction, affective computing

The relationship between cognition and emotion has attracted the interest of philosophers and scientists for centuries[1,2]. Starting with Thomas Aquinas (1225—1274) who divided the study of behavior into two broad categories, cognition and affect[3], cognition and emotion are viewed as separate systems and processes that seldom interact with each other[1]. In the last hundred years, the approach of functional localization has also shaped our conceptual framework of brain function that separates the emotional brain from the cognitive brain[2]. However, the behavioral and neuroscientific data in the past two decades have demonstrated that the notion of functional specialization is problematic. Increasingly more researchers have realized that the processes of cognition and emotion not only interact, but that their neural mechanisms are integrated in the brain so that they jointly contribute to behavior[1,2,4–6].

In the present article, our goal is to summarize the recent behavioral and neuroscientific evidence supporting the interaction of cognition and emotion, and to review the recent accounts on this issue. The main points of the present article are as follows: Firstly, there is an interaction between cognition and emotion not only at the functional level, but also at the neurological level; secondly, the interaction and integration of cognition and emotion is essential to development, and the ability to control emotion at an early age has a significant effect on later development; and finally, the interaction of cognition and emotion may affect many aspects of people's daily activities, including technological innovation. The interaction of cognition and emotion at functional level is reviewed in the first section, the underlying neural regions involved in the interaction are introduced in the second section, and the implications of the interaction between cognition and emotion in daily life are discussed in the last section, especially focusing on the implications for affective computing.

1 The functional interaction between cognition and emotion

Traditionally, cognition was thought to be comprised of mental functions and processes, such as memory, attention, language, problem solving, reasoning, and so on. Many cognitive processes involve controlled and goal-

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oriented processes when the pursuit of a goal needs to be protected from interference[2]. However, it is much more difficult to provide a clear definition of emotion. Some researchers define emotion as drive and motivation[4]. Some researchers focus on the experience of emotion[7]. And others emphasize emotion schemas[8], or the basic emotions[9]. There are a number of different emotional dimensions proposed by psychologists. However, only the Pleasure-Arousal-Dominance Emotional States Model has been accepted by most researchers and has been used broadly in psychology, sociology, and computer science recently[10–12]. There are three nearly independent dimensions in the PAD Model to describe and measure emotional states (or feelings, affective conditions): pleasure-displeasure, arousal-nonarousal, and dominance-submissiveness. “Pleasure-displeasure” distinguishes the positive-negative affective quality of emotional states, i.e. the valence of emotion. “Arousal-nonarousal” refers to a combination of physical activity and mental alertness. And “dominance-submissiveness” is defined in terms of control versus lack of control. No matter how the definition of emotion varies, recent research has demonstrated that cognition interacts with emotion on all the three different dimensions.

1.1 The role of emotion in cognition

The impact of emotion or affect on behavioral performance has been well documented. Traditionally, affect is viewed as a source of irrationality or a kind of bias in human behavior such as attention and decision making[13]. For example, people are strongly influenced by the way in which a question is presented. An operation with 40 percent probability of success seems more appealing than the one with 60 percent chance of failure[14]. Clore and Storbeck[15] further suggested that affective feelings could provide embodied information about value of goodness and badness. By this way, the affective experiences govern our attitudes, and provide red and green lights for different thinking styles. However, recent studies have shown that the effects and functions of emotion on cognition are more basic and complicated than irrationality and bias. One of the most well-known examples is the mood-congruent effect on memory[16]. Emotion can exert effects at the time of encoding, during retrieval processes as well as during the experience of recollection[16,17]. Strong evidence has also been provided that emotion and motivation play a crucial role in perception, attention, executive control, and decision making[15,18–20].

Stefanucci and her colleagues[21,22] found that emotional arousal and valence can influence height perception, and especially, fear can result in height overestimation. People usually overestimated distance and size when they looked down from a high place with trait or state fear of heights[21]. Further research showed that the influence of emotional arousal on estimates of height could be moderated by emotion regulation strategies[22]. If participants were instructed to think of themselves as the central person in emotional situations, they overestimated the height more than did participants who were instructed to think of themselves as in the third-person perspective in emotional situations, and who did not regulate their emotion at all. In addition to spatial perception, several researches also showed that emotional arousal and valence interact to affect the perception of time[23,24], and the emotion-related overestimation of time was moderated by individual differences in negative emotionality[25].

According to many models of attention, objects compete for limited perceptual processing capacity and control of behavior[4,5]. Recent studies further found that visual attention can be voluntarily directed toward stimuli that are emotionally significant[26]. It has been consistently found that negative stimuli captured attention more efficiently than positive stimuli did. Most researches on this topic usually used the paradigm of visual search. Hao et al.[27] used the visual marking paradigm to test the processing advantage of negative expressions, and also found that negative faces were sought much faster than positive faces in a gap condition, but the negative advantage would disappear when the negative faces served as distractors. This research suggests that the emotional significance of the stimuli had a great impact on the visual attention process. Even though the emotional stimuli were task-irrelevant, they were more strongly encoded than the target letters superimposed on them in the spatial competition task[28]. In addition to usual emotional stimuli, Langeslag et al.[18] found that participants paid more attention to stimuli related to their beloved than those related to friends, and the P3 component was modulated by emotion-related factors, as well as task-related factors.

However, research has also shown executive control of attention is more efficient not only in negative situations, but also in positive situations[29,30]. Positive mood is accompanied by a global relaxation of cognitive control that results in a fundamental change in the capacity of selective attention from visual perception to semantic conceptual space[19]. Pessoa[4] proposed Dual Competition Model to describe how affect and emotion influence the flow of information processing. In this model, affective significance impacts the flow of information processing in a stimulus-driven and a state-dependent manner, and in both cases competition is supposed to occur at the perceptual and executive levels. Pessoa[4] pointed out that there are two reasons why emotional stimuli drive executive control: Firstly, strengthened sensory representations with increased visual responses will receive prioritized attention; secondly, affective information may be directly conveyed to the neural structures in which executive control is modulated. Different from stimulus-driven manner, reward-related manipulations of motivation are involved in the state-dependent manner[4].

Another cognitive process related to executive control is working memory. The theoretical concept of working memory assumes that a limited attentional capacity system temporarily maintains and stores information and supports human thought processes by providing an interface between perception and long-term memory[31]. Numerous emotion and working memory studies have found that emotional state or mood influences working memory performance[32]. Baddeley[33] reviewed the effects of danger, elation, anxiety, and craving on working memory, and then he concluded that all of the above emotions appear to disrupt working memory. For example, craving includes mainly positive intrusive thoughts in nature that can result in further elaboration within the episodic buffer, hence reduces the processing capacity of working memory[33]. Therefore, Baddeley[33] proposed a revised working memory model to include the impact of emotional factors on working memory by adding a hedonic detector and episodic buffer.

Since ancient Greek philosophy, rationalists have assumed that emotion can mislead higher cognitive functions, such as rationality and decision making[34]. Based on rationalism, a fundamental assumption of classic economic theory is that people are able to identify and choose what is best for them, conditional on being well informed about their circumstances[35]. However, recent research has found that most decisions are motivated by the pursuit of subjective well-being or happiness[36]. Furthermore, recent findings have shown that people are not always able to choose what yields the greatest happiness or best experience[35]. The reason why people fail to choose optimally is complicated. Hsee and Hastie[35] summarized that either people fail to predict accurately which option in the available choice set will generate the best experience, or they fail to base their choice on their prediction, or both. They proposed two general reasons for the failure. One is prediction bias that occurs because predictors do not fully appreciate the differences between the state of prediction and the state of experience. The other is failure to follow predictions, and this occurs because choosers fail to reach the optimal balance between impulsivity and self-control[35]. The behavioral economic research suggests that people are averse to ambiguity[37]. Researchers propose that dealing with decisions facing ambiguity is a process involving both emotion and reason, and when probabilities are not precise, people are inclined to consider the worst possible outcome of each action they can take as the outcome that will occur[37]. Emotion is also closely related to moral judgment. Several researchers have argued that emotions are the source of our intuitive moral judgments[38]. Although other researchers argue that the current neurological, behavioral, developmental and evolutionary evidence is insufficient to demonstrate that emotion is necessary for making moral judgments, they agree that emotion often follows from the judgments, serving a primary role in motivating morally relevant action[39].

1.2 The role of cognition in emotion

Lazarus[40] proposed that the functional relationships between cognition and emotion are bidirectional, and emotion is the appraisal of the significance of what has happened in regard to personal well-being. Lazarus[40] further states that emotion is always a response to cognitive activity, which generates meaning regardless of how this meaning is achieved. So he believes that cognition is both a necessary and sufficient condition of emotion[40]. Many recent researches provided strong evidence for Lazarus' opinion.

(i) The effect of cognitive processes on emotion. As discussed in Section 1.1, emotional states exert a great impact on attentional processes. The related question in reverse is whether attention affects the experience of emotion. Numerous recent studies demonstrated that attention has a crucial effect on emotional states[41–43]. In the preview search task, the previewed distractors were significantly devalued in the following emotional evaluation task compared with similar nonpreviewed distractors[41]. Furthermore, the distractors presented near the target during researching were rated significantly more negatively than those presented far from the target, and distractors were rated more negatively than the targets[42]. Kiss et al.[20] further found that the efficiency of attentional selectivity could predict subsequent emotional responses, and suggest that attention is closely associated with subsequent affective evaluation of visual stimuli. Fenske et al.[43] also found that prior inhibitory attentional states associated with unfamiliar faces can reduce the trustworthiness of those faces in the subsequent judgments.

The attention effects are so strong that even the stimuli with the same structure as the attended stimuli that the subjects have never seen are rated more positive than the stimuli with the same structure as the unattended stimuli. Zhou et al.[44] adopted a variant of the artificial grammar learning (AGL) paradigm to address this question. AGL is a classical paradigm for the investigation of implicit learning and usually includes a training stage and a testing stage. As shown in Figure 1, during the training stage, participants were required to memorize (i.e. rote learning) some character strings that followed some rule (or grammar); during the testing stage, they were required to classify whether the test items (unseen in the training stage) followed the same rule as those that appeared in the first stage[44]. Most studies using AGL have shown that people can abstract the common complex rule underlying all the memorized items independent of conscious attempts. Therefore, AGL provides a basic rationale for exploring whether the affective consequence of attentional inhibition can be spread to new stimuli from the same family as those inhibited. The findings indicated that the prior attentional states (attended or inhibited) associated with a group of neutral stimuli (character strings) can even influence subsequent preference judgments about previously-unseen stimuli if these new stimuli share certain basic features (e.g., follow the same rule) with those encountered in a previous stage[44].

Other cognitive processes besides attention play important roles in emotional perception and emotional experience. For example, Storbeck and Clore[45] found that the referential processing of negative mood led to accurate memory while the referential processing of positive moods led to false memories. Righart and de Gelder[46] found that there was a response advantage for facial expressions accompanied by congruent contexts under both low and high task load conditions, suggesting that the perception of the surrounding scene plays an important role in recognizing facial expressions. Also, numerous studies have shown that repeated exposures result in the enhancement of subject's preference to a neutral stimulus. Even only mere exposure to a stimulus is sufficient to enhance an individual's liking of it. The mere exposure effect of neutral stimuli has been found to be highly robust, with the effect being found in both children and adults, in field settings as well as in laboratory settings[47]. By using emotionally evocative music as stimuli, Witvliet and Vrana[48] further found that exposure enhanced participants' liking of positive music, but accentuated participants' dislike for negative music. Given the wide applicability and robustness of the mere exposure effect, this link between familiarity and liking has profound application in social science.

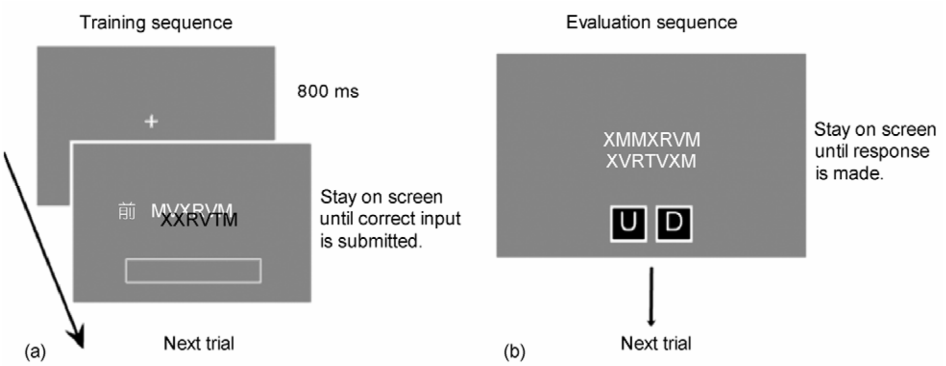

Figure 1 Experimental procedure. (a) Time sequence of a single trial in training stage. The Chinese character on the left of the string pair indicates which string to copy. If the character is "前(it means front)", participants need to type in the string in the foreground. On the other hand, if it is" 后(it means back)", participants need to type in the back one. Participants' input will be shown in the rectangular box below the string pair. (b) Time sequence of a single trial in testing stage. Participants choose the preferred string by clicking either one of the two buttons at the bottom of the screen (U means up, D means down) (ref.[44]).

(ii) The role of language in emotion perception. Traditional facial expression recognition research that follows the basic emotion approach suggests that there are definitely several specific emotion categories that are universal across human races and nationalities[49]. According to the basic emotion approach, the facial expressions are clear and unambiguous, so that the expression is easy for all people to recognize. The perception of emotion takes place automatically and language is not necessary for emotion perception; even young infants can discriminate discrete emotional expressions[50,51]. However, there are many ambiguous situations in daily life that need additional cues to help us judge facial expressions. For example, it may be more difficult to identify emotion of others when there are no exact words to depict it. Recent studies have suggested that semantic information as context cues are necessary for emotion perception, and language intrinsically shapes how one person perceives emotion in another's behavior[49,52,53]. Lindquist et al.[53] found that it would be more difficult to judge the emotions of faces when emotion language was made less accessible via a standard semantic satiation procedure.

Barrett[52] reviews evidence that does not support the basic emotion categories, including the observable properties and the causal mechanism, and further proposed that emotions are not events that broadcast precise information on the faces without any ambiguity. Barrett et al.[49] review research on language as the context of emotion perception, and suggest that language functions as a context in emotion perception to reduce the ambiguity of the structural information in faces. There are two possibilities regarding the role of language in emotion perception[49]. One possibility is that language has its influence at a certain stage of stimulus categorization, where memory based conceptual knowledge about emotion is being brought to bear on an already formed percept[49]. The other possibility is that language contributes to the construction of the emotional percept by dynamically reconfiguring how structural information from the face is processed[49]. It is possible for emotion words to influence how people sample and process the sensory information in a face and construct an emotional percept. Barrett et al.[49] proposed the language- as-context hypothesis, and they believe it will set the stage for future research on how language influences other forms of social perception, such as the perception of gender and race. If conceptual knowledge shapes the perception of social reality and language shapes conceptual development, then language might play a much larger role in shaping our social cognition than previously assumed[49].

(iii) The relationship between expression recognition and facial recognition. The relationship between expression recognition and facial identity recognition has attracted many researchers' attention for many years. The process of facial expression and facial identity that was traditionally viewed as parallel processing is now dubious. Although some researchers still support the independence of the two processes[54], others argue that the two processes interact with each other, and that familiarity with faces increases the perceptual integrality between identity and expression[55]. And recently, more and more evidence tend to support an interactive relationship between the processing of facial expression and facial identity.

Following the research of Bruce and Young[56], Wang and Fu[5] proposed the Face Recognition Functional Model. They focused on the debate about parallel and interactive processing between facial expression recognition and facial identity recognition. They proposed an integrative model (Figure 2) based on the distributed human neural system to illustrate the mechanism of facial expression and facial identity recognition.

The recognition of facial identity is based on the perception of aspects of facial structure that are invariant across changes in expression and other movements of the eyes and mouth[58]. Wang and Fu[59] pointed out that almost all of the past studies neglected to highlight the fact that the intensity variation information of facial expressions might be a very important factor in facial expression recognition. To further test the interaction between expression recognition and facial identity recognition, they manipulated the facial expression intensity by morphing pictures, and found that identity influenced expression recognition but expression did not affect identity judgment when the discriminability of facial expression was low[59]. The results support the hypothesis that facial expression intensity enhances the discriminability of facial expressions, but not that of facial identity, indicating that sometimes the effects of identity on expression recognition can disappear[59]. Zhang et al.[60] explored the role of facial identity in the processing of facial expression by using a visual search task. Participants were asked to search for a happy or sad face in a crowd of pictures of emotional faces. Expression search was more quick and accurate when all faces in a

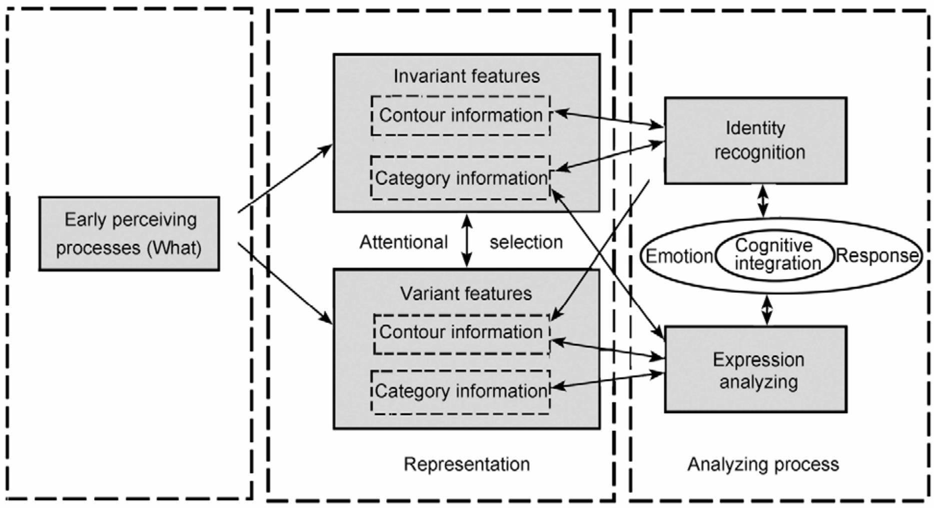

Figure 2 Integrative model (ref.[57]).

display belonged to one identity, compared to when they belonged to two identities, indicating the interference of identity variance in expression recognition[60]. In addition, the search speed of a certain expression depended on the number of facial identities: when faces in a display belonged to one identity, a sad face among happy faces could be found more quickly than a happy face among sad faces; however, when faces in a display belonged to two identities, a happy face could be found more quickly than a sad face[60].

In recent years, there has been an increasing amount of research on the role of eye gaze in facial expression recognition. Eye gaze can provide a number of different cues for social interactions and emotional perception. Adams and Kleck[62] proposed that gaze direction is associated with approach-avoidance behavioral tendencies in that they found that approach-oriented emotions (anger and joy) were processed more quickly with direct gaze, while avoidance-oriented emotions (fear and sadness) were processed more quickly with averted gaze. Graham and LaBar[62] found that gaze direction interfered with expression processing only when facial expression was difficult to discriminate by using Garner paradigm, and they suggest that the processing of eye gaze and facial expressions are only partially dependent. To further investigate the role of facial processing in expression recognition, Shang et al.[63] addressed the effects of gaze direction on the perception of facial expressions, and found that gaze direction influenced the dominance of neutral and angry facial expressions, and averted gaze facilitated the processing of angry faces. These findings suggest that social dominance might be the mediator of the effect of gaze on perception of threatening facial expressions[63].

(iv) The cognitive control of emotion. How should we manage our emotion? Although each culture answers this question differently, there is a common theme: we need to exert some control over our emotions[64]. The capacity to regulate emotion is an important cognitive function for human adaptation, and the regulatory efforts largely determine the impact that some negative emotions will have on our mental and physical well-being[65].

Emotion regulation refers to the processes by which we control which emotions we have, when we have them, and how we experience and express them[66]. Gross[66] proposed five emotion regulation strategies: First, situation selection refers to approaching or avoiding certain people, places, or things so to regulate emotion; second, situation modification refers to problem-focused coping or primary control; third, attentional deployment refers to selecting which of the many aspects of the situation you focus on; forth, cognitive change refers to selecting which of the many possible meanings you will attach to that aspect; and fifth, response modulation refers to attempts to influence emotion response tendencies once they already have been elicited. Gross[66] suggested that the first four are antecedent focused strategies in that these strategies are used before the emotion response tendencies have become fully activated and changed our behavior and peripheral physiological responding, while the fifth is a response focused strategy in that this strategy is used once an emotion is already underway, after the response tendencies have been generated[66]. After a review of findings related to the consequences of reappraisal (i.e. cognitive change) and suppression (i.e. response modulation), Gross[66] concluded that reappraisal and suppression strategies lead to different affective, cognitive and social consequences. For example, suppression appears to have little impact on negative emotion experience but can decrease positive emotion behavior. On the contrary, reappraisal decreases negative emotion experience and expression but increases positive emotion experience and expression.

Ochsner and Gross[65] discuss how recent neural imaging work has investigated two types of cognitive regulation: attentional control and cognitive change. As we mentioned before, attention is often referred to as the selective aspect of information processing that enables us to focus on goal-relevant information and ignore goal-irrelevant information. Attentional control enables us to spontaneously look away from aversive events towards pleasant ones. Some studies have found that amygdala activation decreases when participants attend to and evaluate emotional features, for example, matching emotional faces or scenes based on emotional labels[67]. Ochsner and Gross[65] explain that these judgments might impose a greater attentional load, which strongly limits the processing of perceptual inputs and participants might in some cases actively regulate their responses. Therefore, Ochsner and Gross[65] further divide emotion regulation into behavioral regulation (e.g. suppressing expressive behavior) and cognitive regulation (e.g. attending to or interpreting emotion-eliciting situations in ways that limit emotional responding), and suggest that there are three approaches in which the use of cognitive change to generate an emotional response has been studied: The first approach has examined the neural correlates of anticipatory responses that precede expected emotional events; the second approach has examined the expectations about how a stimulus might influence the neural responses to it; and the third approach has directly contrasted top-down responses generated by beliefs about a stimulus with bottom-up responses driven by direct perception of aversive stimuli.

Although most emotion regulation researches emphasized the importance of decreasing unpleasant emotions, Tamir et al.[68] demonstrated that individuals were sometimes motivated to increase their anger for better performance when engaging in a confrontational task. After a review of recent research findings concerning emotion regulation, Gross[69] concluded that the crucial factor is to use a strategy that matches one’s goal since different emotion regulation strategies have different consequences. Also, he identified three new directions for future research in emotion regulation: First, the role of beliefs in shaping when and how we try to regulate our emotions; second, the largely unexplored realm of automatic emotion regulation processes; and third, the bridges that are beginning to be built between basic research on emotion and emotion regulation, and clinical research and practice. Emotion regulation issues in our lives will further benefit from findings in these research areas[69].

2 The neural mechanisms of cognitive-emotional interaction

It is difficult to summarize the set of brain regions that comprises the emotional brain. Although many researchers claim that some regions are linked to specific affective functions, none of the regions is purely affective. The hypothalamus was first found to be linked to emotion. Pessoa[2] summarizes some regions that are prominently linked to affective functions based on an informal assessment of the frequency with which they appear in the literature. The core emotional regions include, subcortically, the amygdala, the nucleus accumbens, and the hypothalamus, and cortically, the orbitofrontal cortex (OFC), the anterior cingulate cortex, and the ventromedial prefrontal cortex. Extended regions appearing with less frequency include, subcortically, the brain stem, the ventral tegmental area, the hippocampus, the periaquaeductal grey, the septum and the basal forebrain; and cortically, the anterior insula, the prefrontal cortex (PFC), the anterior temporal lobe, the posterior cingulate cortex, superior temporal sulcus, and somatosensory cortex. However, recent neuroscience research has provided strong evidence that most of these neural regions are also involved in cognition processes, and some of them are thought to have a central role in cognition, such as the hippocampus, the prefrontal and parietal cortices.

Pessoa[2] pointed out that it is inherently problematic to divide the brain into cognitive and affective regions based on the current knowledge of brain function and connectivity. The functions and neural mechanisms of cognition and emotion not only interact, but are also integrated in terms of functional organization, even during infancy and early childhood[2,70]. The brain regions traditionally viewed as affective regions are involved in cognitive processes, and the brain regions generally viewed as cognitive regions are also involved in affective processes. Therefore, each cognitive or affective region is involved in a number of functions. In this section, we will review the neuroscience data supporting the interaction and integration between cognition and emotion, and discuss the possible neural mechanism underlying the integration.

2.1 The amygdala

The amygdala is often categorized as an affective region strongly linked to fear processing. However, this structure is also involved in several functions that are closely linked with cognitive processes, including attention, associative learning (even implicit learning), perception of automatic emotional responses, and memory.

The amygdala is crucial to enhancing visual perception of emotional stimuli and also is involved in selective attentional processes[2,4,46,65]. For example, amygdala-damaged rats fail to acquire orienting responses which reflects a failure to increase attention to a cue[71]. Recent studies have provided strong evidence that the amygdala-mediates the processing advantage of emotional items[2]. Lim and Pessoa[72] found that participants had increased sensitivity to shock-paired faces and patches relative to unpaired faces and patches during a neutral/fearful discrimination task, and they were more likely to report the faces and patches as fearful if they were shown in a color that was previously paired with shock.

Accumulating evidence has verified that the amygdala is important for mediating emotional influence on perception. For example, when patients, with either blindsight or visual extinction, were presented with emotional stimuli out of awareness in the damaged hemifield, the amygdala showed activation to these stimuli[5]. Also, in a functional neuroimaging study, using a visual backward masking paradigm, showed that when normal participants were presented with stimuli out of their awareness, the amygdala responded differently to unseen emotional and unseen nonemotional targets[5]. One set of facial expression recognition studies found that when emotional faces were presented to a neurological patient with brain damage to the visual cortex, the patient could discriminate the emotion in the faces by guessing, even he was unable to report seeing the stimuli[73]. A follow-up neuroimaging study found that the amygdala of the patient was activated differently by different emotional faces, despite the absence of conscious visual experience.

There is also considerable evidence showing that amygdala is involved in associative learning. Animals with amygdala damage could not express fearful behavior when a cue that signaled an impending aversive event was presented, and failed to show associations between cues and positive experience[71]. Patients with amygdala damage also could not acquire conditioned fear responses, even though they retained the explicit knowledge about the associations between conditioned stimulus (CS) and unconditioned stimulus (US)[5]. Barot et al.[74] proposed a model to explain how the neurons in basolateral nucleus of the amygdala (BLA) activate during associative learning. The model suggests that when a novel CS is shown, the neuron in the BLA becomes more sensitive to subsequent US input and convergent activation is seen.

By influencing perception and attention, the amygdala can also modulate the encoding of episodic memory about emotional events. Phelps[75] further argued that the amygdala could modulate not only the encoding but also the consolidation of hippocampal-dependent memories. As we mentioned earlier, the amygdala has connections with sensory cortical processing regions, such as the visual cortex. The amygdala might receive information about the emotional significance of a stimulus early when the stimulus is displayed to our perceptual system, and the amygdala's feedback could result in enhanced perceptual encoding for emotional events. After encoding, there is a slow consolidation period in which the memories become consolidated to be stored in the long-term memory. In this period, any emotional reactions to events change hormone levels, making events of greater importance more likely to be remembered. Studies of animal models show that stress hormones activate adrenergic receptors in the basolateral amygdala, suggesting that hippocampal consolidation of memory is modulated by the level of hormones[75].

2.2 The hippocampus

As one part of limbic system, the hippocampus is also thought to be related to emotion. Early studies found that destroying the hippocampus in monkeys had a depressive effect[76]. Based on both animal and human studies, Papez[76] suggests that the hippocampus participates in the central production of emotive process in some important way. However, the research in the last three decades has verified that the hippocampus plays a crucial role in long-term memory, spatial navigation, and other important cognitive processes[77].

Now, it is agreed that the amygdala-hippocampus interaction system is the basic neural mechanism underlying the interaction between emotion and memory. The amygdala influences the encoding of emotional memories in the hippocampus, while the hippocampus forms episodic memories of emotional stimuli and events, and further influences the amygdala's response when emotional stimuli are encountered[75,78,79]. The interactions between the amygdala and hippocampus are necessary not only for the encoding and consolidation of emotional memories, but also for the retrieval of emotional memories[16]. For example, animal studies show that the amygdala and hippocampus synchronize during the retrieval of fear memories and the cooperation of the amygdala and hippocampus was also found in human studies when human participants retrieved fearful memories[16]. Furthermore, hippocampus-dependent memories have significant influence on the activity of the amygdala. For example, an fMRI study showed that when participants were instructed that they would receive one or more mild shocks after a specific cue was presented, they showed activation of the left amygdala during the presentation of the cue even when no shocks were actually presented[75].

2.3 The prefrontal cortex (PFC)

The PFC is critical to the maintenance and manipulation of information. Its lateral aspect (LPFC) plays a key role in the function of executive control[2,4]. Recent research found that the PFC interacts with other brain regions and is also involved in the integration of cognition and emotion.

The connection between the PFC and the amygdala guides attentional resources towards the location of emotional items, and the connections between the PFC, the amygdala and the hippocampus contribute to emotional episodic memories[4]. Gray et al.[80] found that emotional states could selectively influence cognition-related neural activity in LPFC, that is critical to goal-directed behavior and is also sensitive to approach-withdrawal emotion. In their study, participants performed a working memory task with either words or faces as stimuli. Participants were scanned by functional MRI after pleasant states (approach related), unpleasant states (withdrawal related), and neutral states were induced by watching short videos. Their results showed a significant emotion and stimulus crossover interaction for task-related neural activity in the bilateral PFC, and neural activity was consistent with the task performance, providing strong evidence for the integration of cognition and emotion. Moreover, some studies with patients of amygdala lesions show that emotional benefits in memory are still possible even without a fully functioning amygdala[78]. In these cases, the direct interaction between the medial temporal lobe and the PFC may mediate the processing of emotional information[78].

Currently, it is agreed that the PFC is best conceptualized as consisting of many areas, such as the anterior cingulated cortex (ACC), the orbitofrontal cortex (OFC) and the ventromedial PFC. All of them have their specific functions[2]. Next, we will further discuss the role of the OFC and the ACC in the cognition-emotion integration.

2.4 The orbitofrontal cortex (OFC)

The OFC, as part of prefrontal cortex, is a region of association cortex of the human brain. Because of its functions in emotion and reward, the OFC is considered to be a part of the limbic system[2,81].

It has been accepted that the OFC is necessary for reinforcers to exert their normal control over behavior. Some animal studies show that when monkeys learn to choose one of two objects to get a reward, those with OFC lesions are unable to inhibit responding to the previously rewarded item when the contingencies are reversed[82]. Additionally, neuropsychological studies have also shown that patients with the OFC damage cannot alter their choices to avoid losing money after encountering losses[82]. It has also been found that the OFC responds to reinforcement and associated events in single-neuron recording and neuroimaging experiments[81].

Furthermore, recent research has found that the OFC might play a crucial role in the generation and use of outcome expectancies[83]. For example, some neuroimaging studies with normal human subjects have shown blood flow changes in the OFC during anticipation of expected outcomes, and also, when the value of an expected outcome is modified or not delivered, it indicates that this activation may reflect the incentive value of these items[83]. Wallis[82] proposed that the OFC integrates multiple sources of information based on the reward outcome to derive a value mark, and then, behavior toward obtaining the reward outcome is planned and organized in lateral prefrontal cortex, and finally the overall action and the effort being required is evaluated in medial prefrontal cortex.

OFC damage produces an unusual pattern of deficits, in which patients have intact cognitive abilities, but are impaired in making everyday decisions. The role of the OFC in the decision making has attracted attention recently. Beer et al.[84] examined the role of the OFC in decision making with a risk-taking task, in which participants were presented with some negative and neutral pictures before a bet task, and they were required to ignore the pictures or were told that the negative pictures meant that the upcoming bet was more risky. The results showed that not only the relevant negative emotion, but also irrelevant negative emotion increased the activation level of the lateral OFC. Wallis[82] suggests that the OFC is crucial to decision making because it plays a key role in processing reward that can ensure that our behavior is most efficiently directed towards satisfying our needs.

2.5 The anterior cingulate cortext(ACC)

The ACC is also thought of as part of the limbic system[85]. Traditionally, this region has been thought to play a central role in the neurobiology of depression and affective disorders[86]. However, during the last three decades, a number of neuroimaging results indicated that the ACC is also involved in many cognitive pro cesses such as implicit learning, decision making, and attention.

To fully understand the role of the ACC, it is divided into affective and cognitive subdivisions: the affective subdivision encompasses the rostral and ventral areas of the ACC and is involved in regulating visceral and autonomic responses to stressful behavioral and emotional events, emotional expression and social behavior; the cognitive subdivision includes the dorsal regions of the ACC and plays an important role in response selection and processing of cognition[87]. For example, the activation of the dorsal regions has been reported during the processing of competing information, and the monitoring of cognitive or affective conflicts, indicating that the cognitive ACC may serve as an evaluative function, while ventral regions are suggested as crucial to assessing the presence of possible conflicts. Therefore, it is not surprising that the ACC is involved in different anxiety disorder such as obsessive-compulsive disorder (OCD), posttraumatic stress disorder (PTSD), and simple phobia.

The ACC is also involved in the social cognition to understand others' emotion through its connection with the amygdala and others' brain regions[88]. In one recent fMRI study, emotional conflict was tested by the Stroop paradigm, and the results indicated that the amount of emotional conflict was reflected by activity in the amygdala and dorsolateral prefrontal cortices, while the resolution of emotional conflict was associated with activation of the rostral ACC[89]. The activation of the rostral cingulate was predicted by the amount of previous trial conflict related neural activity, and was accompanied by a simultaneous and correlated reduction of amygdalar activity. This suggested that emotional conflict was resolved through top-down inhibition of amygdala activity by the rostral ACC[89]. Other studies also show that ACC is involved in computing the costs and benefits of acting by encoding the probability of reward. Also, the ACC is critical to making decisions about effort costs[2].

2.6 The cerebellum

Traditionally, the cerebellum was thought of purely as a motor control device. However, there is an increasing amount of research showing that the cerebellum contributes to cognitive processing and emotional control in addition to its role in motor coordination[90].

Lesion studies found that patients with cerebellar damage show impairments in executive function, language, and emotion regulation. Also, functional neuroimaging studies have found that visually induced emotion and facial expression recognition increase activity in the cerebellum[91]. To further investigate the role of cerebellar emotion, Turner[91] first combined the use of positron emission tomography (PET) and emotion-inducing probes in patients with cerebellar stroke, and found that patients with cerebellar lesions showed reduced pleasant experience in response to happiness-evoking stimuli despite normal perception of the emotional relevance of the stimuli presented. However, these patients showed normal responses to frightening stimuli similar to healthy controls with significantly lower activity in the right ventral lateral and left dorsolateral prefrontal cortex, amygdala, thalamus, and retrosplenial cingulate gyrus. Unpleasant feelings elicited the "alternative" limbic circuitry instead of normal regions (e.g. amygdala). This finding suggested that alternate neural circuitry became responsible for maintaining the evolutionarily critical fear response after cerebellar damage.

Furthermore, clinical studies yielded strong evidence for cerebellar abnormalities in emotional disorders, including schizophrenia and depression[92]. Neurobiological studies showed that extra-cellular single-unit responses of Purkinje cells in the anterior cerebellar vermis vary as a function of fear learning. These results provided corroborating evidence for the involvement of cerebellum in fear learning, and suggest that the cerebellum is part of a complex system that controls emotional behavior[92,93]. In addition, Transcranial Magnetic Stimulation (TMS) studies have demonstrated that slow repetitive transcranial magnetic stimulation to a subject's cerebellum for several days elicits an increase in negative mood, indicating that emotion regulation is impaired by such stimulation[94].

2.7 Related developmental research

The integration of cognition and emotion is essential to children's development. Based on the integration approach, Wolfe and Bell[70] tried to investigate the relationship between cognitive development and emotional development in the first years of life by examining the interaction between cognitive control (working memory) and emotion regulation (children's temperament). Wolfe and Bell[70] chose 8-month-old infants and 4.5-year-old children as participants and found that the early-learned regulatory and attentional behaviors have great influence on later development, suggesting that it is not infant cognitive performance but infant temperament characteristics that possibly predict early childhood cognitive abilities.

A study of adolescent-onset schizophrenia also showed that cerebral dysfunctions of the emotion-cognition interactions are seen at an early age[95]. For example, during a working memory task that evoked negative and neutral emotions, the areas typically associated with working memory performance were found to be hypoactivated in patients with adolescent-onset schizophrenia relative to the control subjects, including the dorsolateral prefrontal and parietal cortex and the anterior cingulate. However, patients with adolescent-onset schizophrenia mainly demonstrated increased activation in key areas of emotional processing, such as the left OFC and medial frontal areas during negative emotion induction[95]. As we reviewed above, the cognitive control of emotion and the emotional influence on cognitive control depend on the integration of several brain regions, such as the PFC, the OFC, the amygdala and other related regions. These findings further verify that the successful integration of cognition and emotion is central to the quality and range of everyday human experience.

3 Implications

Just as research in psychology has separated emotion from cognition in the last centuries, computer science had also neglected affective factors in intelligent machines for a long time. In 1985, Minsky[96] first pointed out that the question is not whether intelligent machines can have any emotions, but whether machines can be intelligent without emotions. Researchers in computer science have realized that machine intelligence should include emotional intelligence. Emotional intelligence refers to the ability to recognize emotion and is an aspect of human intelligence[97]. However, except the humanoid robots with artificial emotions in science fiction movies, there has been little serious research on emotional intelligence in computers until 1997, when Picard's book *Affective Computer*[98] was published.

Affective computing refers to computing that relates to, arises from, or deliberately influences emotions, especially in human-computer interaction[98]. Affective computing aims to create a computing system with the ability to recognize, understand, express, and respond to human emotion in order to improve human affective experience with technology. Computers are designed to have self-contained, self-sufficient intelligence, and the abilities to influence or to be influenced by human emotions. They can interact with people in a more natural and kindly manner. Affective computing research is of great benefit to both a harmonious electronic society and the development of psychological science.

Affective computing has attracted a lot of attention and research efforts in the past decade as a new cross-discipline. Nowadays, there are a number of labs in the world focusing on the affective computing research, such as MIT Media Lab, The Swiss Centre for Affective Sciences, Tsinghua University, and Institute of Psychology, Chinese Academy of Sciences. They aim at giving computers the ability to sense, recognize, and respond to certain aspects of human emotion, especially affective states such as frustration, confusion, interest, stress, anger, and joy. They have been developing computer systems that are wearable and computers that respond to people with a kind of active listening, empathy, and sympathy.

What are the implication of the research on the interaction of cognition and emotion to affective computing? Despite the fact that emotion is fundamental to human experience, for a long time technologists have largely ignored emotion and created a frustrating experience for people. The ignorance of technologists in part comes from the complicated relationship between cognition and emotion. Fortunately, with the idea of the interaction between cognition and emotion slowly filtering into people's mind, more and more attention has been paid to the role of emotion in computer science.

Designers, engineers and technologists also have begun to realize that emotional factors are important for their products. For example, Norman[99] proposed that attractive products have a better effect, and that the emotional side of design may be more critical to a product's success than its practical elements. With deeper and more detailed research on the interaction of cognition and emotion, the relationship between the two parts of our mind becomes a little clearer. This leads designers, technologists and engineers to pay more attention to how they can create much friendlier human-computer interactions. The research also helps to develop new technologies and theories that advance the understanding of emotion and its role in human experience, and to reach a proper balance between emotion and cognition in the design of technologies for addressing human needs.

However, it is not easy to fulfil affective computing goals because of the complicated emotional phenomena. For example, although various researches of affective computing have been reported in international journals and at international conferences, unfortunately, computational models for representing and measuring emotions, one basic research aspect of affective computing, have rarely been addressed. Research efforts are mainly focused on the recognition of the six basic or typical emotions, whereas psychological evidence has shown that the emotional states can be represented in nearly three orthogonal dimensions. For example, based on psychological findings on the PAD emotional state model[10–12], Tao et al.[100] proposed a computational method to analyze the diversity of the PAD data collected from well-designed psychological experiments, and to build the model adapting to the data at the same time. Our primary experiments have shown that the emotional states can be represented and measured in the positions relative to PAD axes in a PAD-based three-dimensional coordinate system (Figure 3).

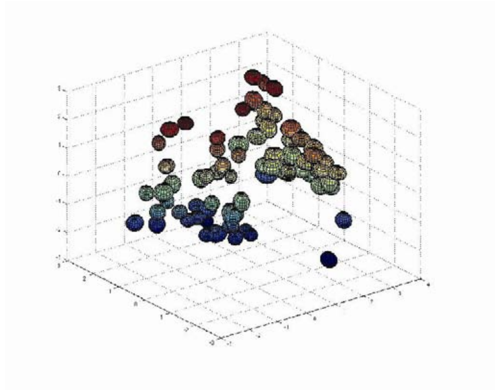

Figure 3 The 80 Gaussian models of 80 scenarios. The three coordinates are P, A, and D. The center of an ellipsoid is the center of a data distribution, and volume of an ellipsoid represents the variation of the data set (ref. [100]).

Despite great difficulty, some researchers have provided evidence supporting the basic idea that the interaction between cognition and emotion can be applied to intelligent computer systems for expression recognition and emotion training. For example, Niedenthal[101] found that the embodiment of emotion causally affects how emotional information is processed when induced in human participants by manipulations of facial expression and posture in the laboratory. Comprehension of the emotional communication was facilitated by the congruence between the recipient's bodily expression of emotion and the sender's emotional tone of language, but was impaired by the incongruence between them. They found that individuals reported that they experienced the associated emotions when they adopted the congruent emotion-specific postures, suggesting individuals' preferences and attitudes were influenced when they adopted facial expressions or made emotional gestures; but their emotional experience was interfered when their motor movements were inhibited. These results suggested that perceiving and thinking about emotion involves perceptual, somatovisceral, and motoric reexperiencing of the relevant emotion in oneself.

Research on expression recognition also has implications for intelligent systems, especially research on the relationship between eye gaze and facial expression. As we mentioned above, eye gaze plays an important role in facial expression recognition. Eye gaze is an important cue for automatic expression analysis systems to use in order to recognize facial expressions[63]. There are some systems such as the Automatic Face Analysis system that analyze facial expressions based on facial features. Gaze direction is a critical factor for these systems to recognize expressions more efficiently[63]. In virtual environments, people get to know others' emotions and intentions through the avatar's gaze, and eye animations have a positive effect on participants' responses to an immersive interaction. Similarly, eye contact is also critical to human-robot communication[63]. When generating animated men or robots with the ability to recognize or express human emotions, gaze direction should be taken as a facilitator to make avatars more expressive for communication in virtual environment, and to make human-computer and human-robot interaction more effective[63].

In conclusion, the interaction between cognition and emotion is basic for human adaptation to the environment. In this paper, we firstly summarized how the processes of cognition and emotion interact with each other, then reviewed the possible neural substrates for the cognitive-emotional interaction, and finally discussed how the interaction of cognition and emotion might affect computer science and artificial intelligence, especially focusing on the implications for affective computing. However, it is worth noting that although recent studies have provided strong evidence in support of the interaction between cognition and emotion and some related findings have been applied to daily life, there are still a number of problems unsolved that need future investigation. Firstly, which is the fundamental function for human survival, cognition or emotion? Secondly, how could our emerging understanding of the interaction between emotion and cognition be extended to social psychology and psychopathology? Thirdly, how might the interaction of emotion and cognition influence human development from birth, and is there any method that can optimize human potential? Finally, how might research on the relationship between these two parts of our mind help solve these complicated problems, and lead to creative methods that can make human-computer interaction friendlier?

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