Chapter 6
Emotional Cognitive Mechanisms for Embedded Systems

A cognitive embedded system is an embedded system that takes advantage of cognitive processes to propose intelligent solutions.

It is strongly perceived that the future of intelligent embedded systems is oriented towards the implementation, either in software or hardware, of cognitive mechanisms. However, the predicted future is not something will happen decades from now. Since adaptation, namely the ability to automatically modifying the system to host a new situation, is a basic form of cognition associated with elementary automatic reactions, we can safely claim that the future of embedded systems has started already. In fact, many embedded solutions present in the market introduce adaptation mechanisms at various levels (see Chap. 8). At the same time, technological advances in the hardware both at the microprocessor, FPGA and Graphics Processing Units (GPU) level make available a computational power that permits the execution of sophisticated embedded solutions also integrating online learning and cognitive mechanisms.

This chapter aims at providing an engineering-oriented perspective of brain functions. Obviously, from a biological view point, most functions are not done by a specific region, but emerge over many regions through natural neurodynamics. Nevertheless, the spirit of this chapter is to apply "lessons" from the brain to embedded systems (and not to duplicate the way the brain works). More specifically, the chapter introduces a functional description of some basic processes of the human brain, with a special focus on emotional and cognitive processing. Emotion processing is, in fact, a complete framework that enables most of the fundamental data processing and storage elements modellable with automatic and controlled processes and, as such, it represents an ideal candidate to be mimicked. Access to the memory to retrieve/store information is a key function here, with information "stored" in different ways, from simple patterns associated with feature instances to more advanced forms of semantic knowledge.

We anticipate that many mechanisms introduced in subsequent chapters, e.g., those related to PACC, adaptation, and learning in a non-stationary and evolving environments can be immediately cast within a cognitive representation of emotions.

C. Alippi, *Intelligence for Embedded Systems*, DOI: 10.1007/978-3-319-05278-6_6,

As such, each of those chapters will have a section showing how the presented methods are modellable as instances of the emotional cognitive processing. However, it is worth outlining that the association "emotional processing-intelligent algorithm" finds affinity in other neural cognitive mechanisms. We leave the interested reader to deepen the investigation in reference textbooks, e.g., see [220] for a recent essay on neural anatomy and information processing and [221] for cognitive aspects.

6.1 Emotional Cognitive Structure

Brain phenomena can be modeled as a hierarchy of subsystems differentiating in time activation and accuracy levels [138–140] that, possibly, rely on a memory containing knowledge suitably stored for decision making and supporting other processes.

Lower levels are generally characterized by fast automatic processes so as to be able to quickly take a decision and/or provide a prompt reaction following the presentation of external stimuli. In the meanwhile, either these processes or the presence of stimuli activate higher levels of knowledge processing characterized by more complex and articulated controlled mechanisms able to assess ongoing performance and abort/modify/complete actions and decisions made by lower levels. Not rarely, higher cognitive levels introduce feedback mechanisms by providing information to lower ones so that learning can be perfected, e.g., through a fine tuning of the existing schemata. Clearly, new situations encountered during lifetime must be included in the processing mechanism and stored in the semantic memory where long-term knowledge is kept.

The joint activity of automatic and controlled processes allow us for modeling the emotional responses in humans. Here, lower levels provide immediate actions following a stimuli pattern presentation. Clearly, promptness in the reply i.e., low latency in pattern classification and decision making, is to be preferred than high accuracy in emotion labeling: if a potential threat is somehow detected we need to immediately intervene instead of waiting for more information to come or the outcome of a more sophisticated, and hence time consuming, processing. Higher processing levels will then be activated either from available stimuli, so as to permit a parallel processing, or be initiated by automatic ones. In both cases, the goal is to assess the action taken by lower levels and intervene whenever appropriate to confirm, abort or correct the decision made.

In the last decades there has been a lot of work on emotional processing, much is known, but a complete understanding of automatic and controlled cognitive mechanisms is still missing.

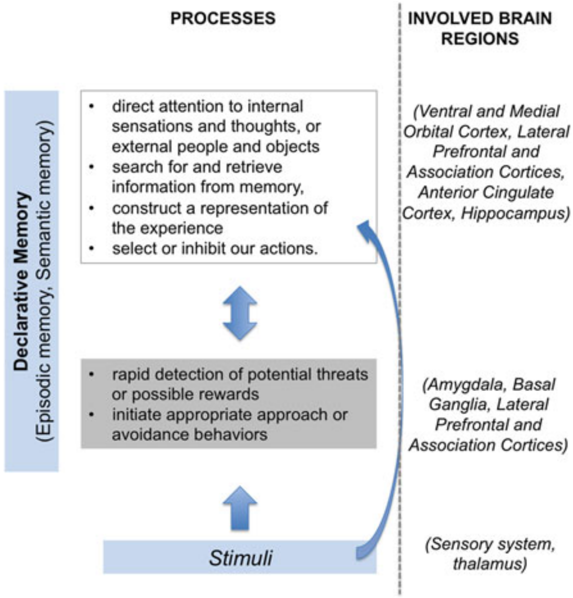

Fig. 6.1 Automatic and controlled processes and involved brain regions

6.2 Automatic and Controlled Processes

Automatic and controlled processes involved in emotional expression processing and response activation are briefly described in the following with Fig. 6.1 representing the reference framework. The interested reader can refer to e.g., [140] for a more detailed analysis of the presented concepts.

6.2.1 Automatic Processes

Automatic emotion processes, that refer to the lowest levels of the hierarchical cognitive system, are characterized by an interesting and relevant detection-reaction mechanism designed to quickly identify potential dangers and the possibility to get a reward and initiate suitable actions/reactions, e.g., by increasing the heartbeat or the respiration rate and releasing stress-hormones following a perceived threat. Here, reduced latency is more important than keeping under control the false positive rate following a conservative primordial principle. In fact, it is much better to react with an unnecessary action following a perceived—possibly new—threat than being insensitive to it.

These processes are meant to be quick and effortless in generating an emotional response (which could be either positive or negative) to external stimuli such as presentation of faces, objects or events [140]. This emotional response is part of the emotion processing and the associated decision making level, which involves the detection of danger or plan and schedule actions to get a reward, the recall of previously acquired information related the situation/event/emotion and the activation of a proper action/reaction. It is worth noting that the emotional response (possibly together with additional environmental information) is then processed to become part of the knowledge (i.e., stored in the memory) to be recalled whenever necessary.

By inspecting Fig. 6.1 we see that automatic processes receive stimuli made available by the sensory system or the thalamus and provide outputs to feed controlled processes, which also influence automatic ones with a feedback mechanism. Clearly, we must also react to a threat by activating the sensory-motor mechanism primarily implemented by the sensory-motor cortices, basal ganglia and cerebellum and not considered here being outside the strict emotion processing analysis.

The main tasks carried out by automatic processes can be summarized as

- Rapid detection of potential threats and activate avoidance behaviours;
- Initiate appropriate approaches oriented towards the achievements of rewards.

6.2.2 Controlled Processes

Consciously, we also direct attention to our personal sensations, construct our emotional background, and select or inhibit actions depending on a lifetime experience. The use of computationally demanding processes in the generation and regulation of emotions is named *controlled emotion processing*. By deliberately monitoring, activating and processing emotions we can re-interpret and alter their meaning (learning mechanism), change the current personal experience and perception of the world as well as the way we interpret emotions and respond to stimuli.

After a preliminary automatic response, cognitive processes are consciously activated by higher levels of the cognitive hierarchical system. The aim of these processes is to integrate, improve and (if necessary) correct the output provided by the automatic processing level. As such, these high-level processes allow the human brain for consciously focusing our attention to a specific stimuli or emotion, recalling events or sensations stored in the memory or modifying the action/reaction pattern activated by lower cognitive levels. Differently from automatic processes, this "validation" step is not automatic, is time and energy consuming and requires consciousness.

Moreover, a relevant activity performed by controlled processes is their capability to create an abstract representation/meaning of experienced events or stimuli. These representations, coded in a suitable way, can then be stored in memory and recalled whenever necessary.

With reference to Fig. 6.1 we see that controlled processes receive information directly from incoming stimuli as well as the output of automatic processes. The declarative memory plays a fundamental role being present both for automatic and controlled processes to provide episodic and semantic memory instances to be retrieved, stored or updated. The main tasks carried out by controlled processes can be summarized as

Table 6.1 Roles, functions and characteristics of brain regions. Refer to [138] for a more complete treatment

Brain regions	Function	Operations	Type of process
Amygdala	Detecting, learning about stimuli	Detects potentially threatening stimuli and associates them with appropriate actions	Automatic
Basal ganglia	Registering rewards, acquiring habits, selective gating of behavior	Mediates selection and initiation of actions, automatizes sequences of behavior and reinforced thoughts	Automatic or controlled
Lateral pre-frontal/association cortices	Retrieving and storing semantic emotion knowledge	Identifies stimuli, differentiates feeling states; attributes emotional qualities to stimuli; repository of regulatory strategies, lay emotion knowledge	Retrieval can be automatic or controlled
Anterior cingulate cortex	Conflict monitoring	Monitors on-going behavior and determines whether a change is necessary or not	Conflicts detected automatically, but making changes takes control
Ventral/Medial orbital frontal cortex	Context- dependent action selection	Inhibits on-going emotional responses based on analyses of context	Controlled
Hippocampus	Long-term strategies	Understanding spatial relations within the environment	Controlled

- Select or inhibit the actions activated by automatic processes;
- Construct a representation of the emotional experience over time and perfect it according to the received external stimuli and the final situation outcome;
- Direct attention to internal sensations and thoughts;
- Search and retrieve information from the declarative memory.

6.3 Basic Functions of the Neural Emotional System

Evidences from multiple domains suggests that emotional processing is carried out by at least six distinct neural subsystems. Amygdala can be associated mainly to automatic processes; Anterior Cingulate Cortex, Ventral and Medial prefrontal, Orbital Cortices and Hippocampus to controlled processes, while Lateral Prefrontal and Association Cortices and Basal Ganglia to both [138–141].

The above subsystems differ both in the mechanisms they rely upon and the carried out tasks: their joint interaction is a primary ability of the human brain in emotion processing. Roles, functions and characteristics of these brain regions are summarized in Table 6.1, derived from [140] and here suitably expanded. The functional description of these brain regions are summarized in the sequel. The interested reader can find a more detailed description e.g., in [140].

6.3.1 Amygdala

The role of the amygdala is quite complex and involves the detection of a threat by inspecting stimuli patterns and activating a reaction. Moreover, it helps in modulating the long-term memory consolidation of stimuli-stimuli and stimuli-response association in the emotional declarative memory.

The capability to quickly identify potentially threatening events is crucial for survival purposes and is preparatory for any subsequent action following the detection. The amygdala is devoted to this aspect by assessing the risk associated with acquired stimuli patterns and, if necessary, it activates the proper reaction. Any novel or ambiguous stimulus might initially be intended as threatening within a conservation of species principle, and thus warrants a response from the amygdala even if later the event would be consciously labeled as a false positive based on further information processing.

Among the areas composing the amygdala, the activation of physiological responses (e.g., increase of the heartbeat or respiration rate and release of stress-hormone) is managed by the central nuclei.

6.3.2 Long-Term Memory

The creation and association of long-term memory to emotional events is another relevant activity carried out by the amygdala. Specifically, as pointed out by several researches, the basolateral complex of the amygdala is deeply involved in the association of threatening stimuli with the long-term declarative memories. Moreover, although these mechanisms are not fully understood yet, the amygdala is thought to have a relevant role in the consolidation of long-term (potentially lifelong) memory suggesting the idea that emotions are involved in the long-term storage of perceived events/stimuli. In fact, recent studies suggest that, while the amygdala is not itself a long-term memory storage site, and learning can occur without it, one of its roles is to regulate memory consolidation in other brain regions. This suggests that the amygdala contributes to the development of semantic knowledge by influencing the information incorporated into the long term semantic memory.

Having the above in mind, the amygdala may be considered as a module processing stimuli patterns to detect threats. Since novel and unknown stimuli are initially considered as threatening, amygdala enters into an "alarm" state following their detection. Afterwards, other mechanisms intervene e.g., the anterior cingulate cortex to provide, if required, a new assessment for the threat label recommended by the amygdala. All these aspects are aligned with change detection tests and will be deeply investigated in Chap. 9.

6.3.3 Basal Ganglia

Research indicates that basal ganglia provides functions related to the voluntary motor control (e.g., eyes control) as well as emotional processing, for instance that leading to learn routine behaviors to attain rewards.

Generation of sequential steps for attaining a goal is of paramount importance to achieve rewards requesting an activity planning. Research demonstrated that this task is not carried out within the amygdala but in the basal ganglia. Specifically, although the basal ganglia are involved in sequences of actions and have been proposed as learning such "chunks" [247–249], the sequential aspect is seen as the main function of basal ganglia. Rather, they facilitate action selection, which is important for both sequential and non-sequential response. The function of actually discovering and configuring action sequences is thought to occur in the cortex—mainly the supplementary motor area of the motor cortex [140]. Once a sequence is found to be important enough to be learned as a single action, it is chunked and then gated through the basal ganglia.

In intelligent embedded systems this activity refers to the ability of modeling time dependent events by means of dynamic systems or machine learning techniques (e.g., Markov processes) as done in Chap. 10. The availability of these models is crucial for forecasting purposes and to define sequences of actions necessary to achieve a long-term goal by means of planning.

6.3.4 Lateral Prefrontal and Association Cortices

The lateral prefrontal and the association cortices (LPAC) provide mechanisms enabling the storage and retrieval of semantic emotion knowledge as well using the memory content to asses the relevance of stimuli and events. As such, the role of this subsystem appears to be that of storing emotional concepts and providing mechanisms to connect different memories characterized by similar emotional associations. Access to this emotional database is automatic during the generation of an emotional state, or when we consciously represent or label emotional states to draw inferences about those emotions we are experiencing. However, it is not sure if these brain areas are responsible for emotion labeling.

Although the neural mechanism behind these behaviors is not fully understood, there is evidence that the lateral prefrontal and the association cortices are involved both in supporting the emotional automatic and controlled processes. In particular, the research has found that this system is part of the automatic generation of an emotion in response to external stimuli and that, over time, the relevant regularities of our episodic memory slowly become incorporated into the database of semantic knowledge. We saw that the emotional contents of the semantic memory are influenced by the amygdala, which facilitates long-term consolidation of episodic memory for significant, arousing events.

The lateral prefrontal and association cortices are closely related to the knowledge acquired during the operational life by recurrent adaptive classifiers discussed in Chap. 9. This knowledge is organized into concepts, each of which represents a memory of the state. Similar concepts can be fused together to improve/integrate the knowledge over time.

6.3.5 Anterior Cingulate Cortex

The role of the Anterior Cingulate Cortex (ACC) is to assess the "congruence" of emotions and feelings that have been generated in response to external stimuli. Moreover, the ACC is involved in forecasting whether external stimuli would induce threats or pain in the future or not. This capability, which is conscious, is crucial in the activity planning to achieve long-term goals.

The ACC activity, fundamental in a complex, high-connected systems such as the human brain, is conceptually very close to the validation procedure of hierarchical change detection tests introduced in Chap. 9: in response to an event, signals are jointly evaluated to determine whether what perceived is associated with a false alarm (congruence among stimuli) or, differently, it represents a true change to be taken into account.

6.3.6 Orbital and Ventral-Medial Prefrontal Cortices

The orbital and ventral-medial prefrontal cortices known as OFC and VM-PFC (both simplified in VM-PFC in the sequel) appear to represent the current, context-specific, emotional value carried by an external stimulus and provide functions that allow us to both alter our emotional responses based on analyses of the current context and generate affective responses based on these analyses. These two functions form the foundation for the active regulation of emotion and emotion-guided behavior.

As such, the role of the VM-PFC is closely related to the active approach modeling the human behavior. Emotions, stimuli and memory patterns automatically generated by lower cognitive levels are integrated and linked to the long-term memory to define a "cognitive" high-level response. This response, which could consider and take into account long-term goals, can integrate (or even substitute) the automatic response taken from lower levels. Interestingly, researches (e.g., [138]) found that the "cognitive" ability of the VM-PFC resides in the capacity to connect the memory systems (which include the working and declarative memory) with emotional systems (where the amygdala comes into play) to evaluate the taken actions and recall associated somatic states.

In the field of decision-making [141], the activity of the VM-PFC has been widely and deeply studied. Research demonstrated that damages in the VM-PFC prevent the human brain from effectively integrating information coming from external stimuli, emotions and memory. The effect of this damage induces extremely poor decision-making abilities.

In the context of intelligent embedded systems, this approach is very close to cognitive analysis in distributed fault diagnosis systems where low level information is integrated and analysed by taking into account also the network topology to be able to distinguish between false alarms, real events associated with faults or model bias associated with the models introduced to describe the physical phenomenon under monitoring, see Chap. 10.

6.3.7 Hippocampus

The hippocampus is an old structure of cerebral cortex that takes part in many declarative memory functions which refer to the memory of facts and events. Encoding and recalling information from the memory are the two main tasks of this fundamental subsystem. Interestingly, the hippocampus interacts with the amygdala in the formation of short-term memory, which is a preliminary step for the storage of long-term information. Research demonstrated that lesions affecting the hippocampus induce errors in the processing of information present in short-term memory solely and do not influence knowledge previously stored in the long-term one.

The role of hippocampus in spatial representations is rather clear in the case of rodents. Differently, in primates, it seems to have roles in declarative memory and perhaps sensory integration (though that seems to happen much more in the parietal cortex).

Thought concept formation is much more likely to happen in other parts of the cortex (especially other parts of the temporal lobe and perhaps in the prefrontal cortex), the hippocampus is needed for memory recall only for some period after the memory is first acquired [250]. In intelligent embedded systems, the role of the hippocampus can be associated with the ability to recall previously acquired concepts whenever necessary (refer to Chap. 9).

6.4 Emotion and Decision-Making

Decision-making involves the orchestration of multiple neural structures and cognitive subsystems, e.g., VM-PFC, amygdala, LPAC, and hippocampus [138]. The key reference for understanding this mechanisms is Fig. 6.2.

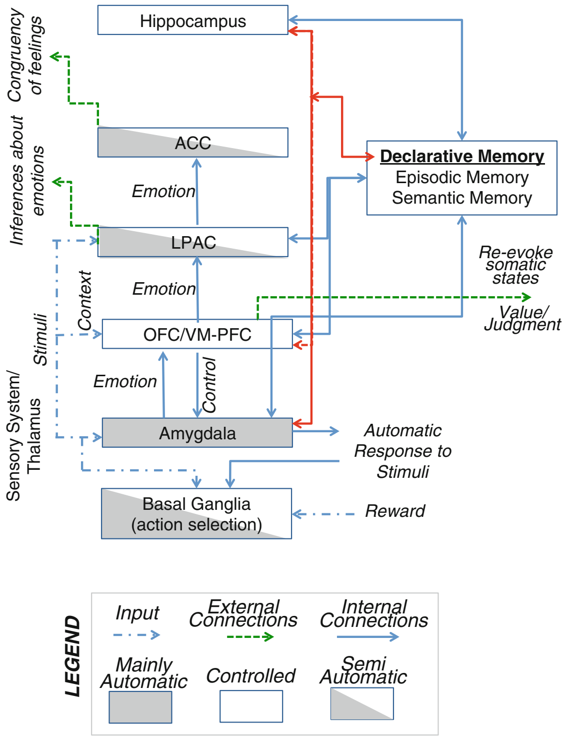

Fig. 6.2 The basic functional elements behind emotion and decision-making in emotion processing

Research has shown that areas such as the VM-PFC, the amygdala, the insula, the somatosensory cortex, the dorsolateral prefrontal cortex and the hippocampus are all involved in various aspects of decision-making [138].

Sensory information is acquired/processed by the sensory system/thalamus and forwarded to amygdala, OFC/VM-PFC and LPAC together with contextual information. Emotions are processed, integrated and abstracted in the processing flow starting from the amygdala and ending with the LPAC, while the congruency of these feelings/emotions is assessed in the ACC. The memory of events/emotions/decisions then come into play through the hippocampus and the VM-PFC together with information about the reward (provided by the basal ganglia) and the value/judgment (provided by the VM-PFC). All these mechanisms cooperate and constitute the basis of the decision-making process.

Interestingly, this complex process is very close to the processing in adaptive classifiers (Chap. 9) where an initial decision is initially taken by considering external stimuli and previously acquired information.