Cogn Comput (2010) 2:78–85
DOI 10.1007/s12559-010-9034-7

Cognition and Emotion: Perspectives of a Closing Gap

Claudius Gros

Published online: 16 March 2010

Abstract The primary tasks of a cognitive system are to survive and to maximize a life-long utility function, like the number of offsprings. A direct computational maximization of life-long utility is however not possible in complex environments, especially in the context, of real-world time constraints. The central role of emotions is to serve as an intermediate layer in the space of policies available to agents and animals, leading to a large dimensional reduction of complexity. We review our current understanding of the functional role of emotions, stressing the role of the neuromodulators mediating emotions for the diffusive homeostatic control system of the brain. We discuss a recent proposal, that emotional diffusive control is characterized, in contrast to neutral diffusive control, by interaction effects, viz by interferences between emotional arousal and reward signaling. Several proposals for the realization of synthetic emotions are discussed in this context, together with key open issues regarding the interplay between emotional motivational drives and diffusive control.

Keywords Diffusive emotional control · Synthetic emotions · Cognitive system theory · Motivational problem

Introduction

The apparent dichotomy between the progression of human cognitive achievements during the last millenia and the pervasiveness of affective behavioral patterns in everyday life has fascinated philosophers from the beginning of times and is subject to libraries of literature. Quite often it is assumed in this context that the emotional groundings of human behavior are somehow a leftover heritage from our more 'animal-like' predecessors and that 'rational behavior' is more appropriate for humans and 'superior' to affective conducts.

This popular appraisal of emotions is however utterly wrong, since emotional control has functional purposes which are indispensable for full fledged cognitive systems and which cannot be substituted by cognitive information processing. We review here our current understanding of the human emotional control system, from the functional point of view, including considerations from dynamical systems theory. The emphasis will be on general properties, being of possible relevance not only for the understanding of the brain but also for eventual human-level artificial intelligences.

The emotional control system is, from the evolutionary perspective, a specialization of homeostatic control. Myriads of auto-regulative processes are maintaining our bodily functions at every moment, and we are conscious of only a small subset having an emotional context. The question then arises which traits are characteristic for automatic and which for emotional homeostatic processes. In this context, we discuss a recent proposal suggesting that emotional processes have a genetically determined preferred level of activation and are characterized by interaction effects within the homeostatic control system, whereas neural control processes are void of any genetically preferred levels of activation.

Functional Emotions

We are around nowadays only because our ancestors managed to survive and to produce offsprings, the basic

C. Gros (✉)
Institute of Theoretical Physics, J.W. Goethe University
Frankfurt, 60054 Frankfurt/Main, Germany
e-mail: gros07@itp.uni-frankfurt.de

prerequisites for evolutionary fitness. Daily survival can be regarded as a homeostatic process for keeping the basic bodily parameters, via interaction with the environment, in their proper range. Being a product of evolutionary selection processes, the emotional constituents of our self must necessarily contribute to survivability [1].[1] One can therefore classify the overall functionality of our emotional control system as homeostatic [2, 3].[2]

The perspective of this short review is the functional role of emotions. Instead of the plain expression "emotions" we will be using mainly the terminology *"emotional control system"*, which reflects more precisely the functional role of emotions as part of the homeostatic control system of the brain. Emotions are part of the web of physical and biochemical processes occurring which, as a whole is denoted *"cognitive system"* [4]. The cognitive system has the task to keep its support unit (the body) alive, as well as its wetware (the brain). A cognitive system is what has been called 'organismic' in the framework of enactive artificial intelligences [5, 6]. The term cognitive system places then emphasis on the dynamical system perspective; the physical brain tissue is not identical with human consciousness and affection, but the collection of interacting neural, physical and chemical dynamical processes occurring at every moment of time.

Natural and Synthetic Emotions

An extensive literature is devoted to the question of the introperspective content of emotions as they are experienced, see [7]. The spectrum of emotional experiences is vast, ranging from plain fear conditioning [8] and romantic love [9], to the complexity of social interactions [10, 11]. Emotional expressions play a paramount role in social interactions [12] and are studied increasingly in the context of human–robot interactions [13]. These important issues are not the subject of this review, they are however closely related to the core questions regarding the defining functional characteristics of emotional processes.

It is clearly possible to build humanoid robots showing facial expressions, which an anthropomizing observer would interpret as emotional [14, 15]. Emotional expressions by socializing robots may be helpful for human–robot interactions but clearly do not correspond to true 'synthetic emotions', which need to be related to behavioral control [16–18], the focus of the present review.

Homeostasis and Diffusive Control

An essential aspect of the living condition is homeostasis, the active regulation of biological relevant parameters, like the blood-sugar level or the heart beating frequency. Homeostatic regulation is also necessary for the internal parameters of individual neurons, like membrane conductivities or firing thresholds, as well as for networks of neurons [19]. The availability of the neurotransmitter glutamate and GABA, to give an example, has to be regulated through a homeostatic cycle involving the astrocytes [20].

Complex dynamical systems, like the neural net in the brain, need to retain their overall dynamical properties in a suitable range, they need to adjust their working point [4]. The occurrence of epileptic seizures is an example of what can happen when homeostasis breaks down. In addition to the homeostatic regulation, necessary to retain operationability, neural circuits in the brain also need to allow for transient modulatory adaption [21]. This second type of regulation allows the neural circuits to work in several different regimes, increasing e.g. the relative importance of afferent input [21] or the relative importance of inter-neural competition [22].

Homeostasis is fundamentally diffusive in nature. The need to regulate the concentration of a given ion or of a certain neurotransmitter is normally performed non-locally. We are interested here, with regard to the functional role of emotional control, in the diffusive control of the properties of neural circuits by neuromodulators like dopamine or serotonin.

Neurobiology of Emotional and Diffusive Control

We will now discuss a few selected aspects of the neurobiology of emotions relevant for understanding the functionality of emotional control. Our aim is however not to provide an extensive review of the neurobiological foundations of emotions, for comprehensive reviews on the subject see [8, 23, 24].

The neurobiological foundations of emotions are neuromodulators like dopamine, serotonin and the ophids [25]. These neuromodulators are emitted by specialized neurons originating in quite localized subcortical structures, like the raphe nucleus and the substantia nigra, ascending to cortical areas, in particular to the prefrontal cortex, as well as to sub-cortical areas like the amygdala and the hippocampus, to mention a few exemplary target areas. Emotional experiences, involving complex recurrent

[1] Subject to evolutionary pressure are all traits which influence Darwinian fitness. An emotional arousal typically leads to behavioral consequences and behavior is a primary toehold for evolutionary selection. This evolutionary perspective sometimes contrasts with our daily experiences, as certain human emotions are routinely viewed to be more a handicap, instead of being beneficial, when living in modern societies.

[2] One may actually wonder, against the background of the fact that our emotional suit contributes in important ways to our Darwinian fitness, why then are emotions portrayed often as irrational and counterproductive in everyday life.

interactions with cognitive processing [26, 27], are not identical with neuromodulator concentrations, but there is probably no fragile or robust emotional experience without the concurrent release of some combination of neuromodulators.

A neuromodulator, like dopamine, is released synaptically. A dopaminergic neuron fires, like any other neuron, and the depolarization pulse travelling along its axon activates the dopaminergic synapses alongside its way. The number of dopaminergic neurons is rather small, e.g. there are about 7,200 dopaminergic cells in the substantia nigra, each one having on average about 370,000 synapses [28]. This very large number of synapses per single dopaminergic neuron indicates that the release of dopamine produces a diffusive volume effect. Cells in the target area have appropriate receptors on their membrane which will change certain membrane properties when activated.

Diffusive, Modulatory and Cognitive Control

Neuromodulators take their name since they modulate the behavior of the neurons in the target area. Within control theory, the term "modulation" generally just implies that the control effect is relatively weak with respect to the eigendynamics of the target, viz modulating and not driving. Here, we will use the term "modulation" in a more restricted sense, with a sharp and qualitative distinction between modulatory and cognitive control.

In Fig. 1, we illustrate the difference between modulatory and cognitive influence and control. For concreteness, let us assume that a typical neuron in the network layer of Fig. 1 has a sigmoidal activation function,

$$\sigma(r, \beta, \theta) = \frac{1}{e^{-(\beta r - \theta)} + 1},$$

with an activation threshold θ. The gain β encodes the steepness and r the cognitive input,

$$r = \sum_{i \in \text{input}} w_i x_i + \sum_{j \in \text{control}} v_j y_j, \tag{1}$$

where the $\{x_i\}$ and the $\{y_i\}$ are neural activity levels of the input and the control layer respectively and the $\{w_i\}$ and $\{v_i\}$ the respective synaptic strengths. Alternatively, the parameters of the activation function $\sigma(r, \beta, \theta)$ of the network-layer neurons might be modulated by the control layer,

$$\beta = \beta(y_1, y_2, \ldots), \qquad \theta = \theta(y_1, y_2, \ldots). \tag{2}$$

We can now clarify the different forms of possible controls.

– **Cognitive control** The neurons of the control layer influence upstream layers in the same way as any other input, compare Eq. (1), e.g. via glutamergic synaptic connections.

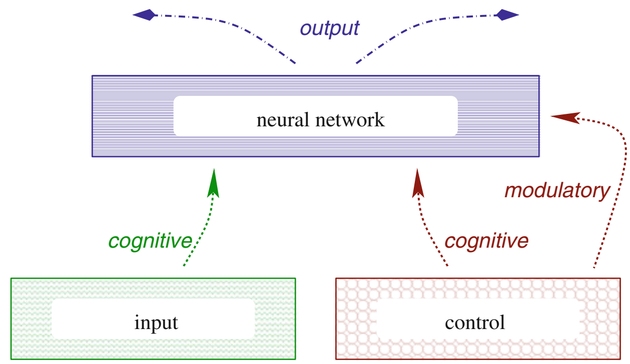

Fig. 1 The difference between cognitive and modulatory control. A neural network is driven by an input layer and its functional behavior regulated by the control unit. For the same stimulation pattern from the input layer different outputs are possible, depending on the signals it receives from the control unit. When a control signal influences the network neurons via direct synaptic connections, the control is cognitive; if it affects the parameters of the network neurons (*dashed line with open head and tail*), like the firing threshold or the gain, see Eq. (2), the control is modulatory.

– **Modulatory control** There are no direct (e.g. glutamergic) synaptic connections from the control layer to upstream layers, viz the $v_j \equiv 0$ in Eq. (1). The influence on upstream layers occurs exclusively via the (e.g. dopaminergic) modulatory influence on the internal parameter of upstream neurons, as in Eq. (2).

– **Diffusive control** Diffusive control is modulatory. Modulatory control could still be target specific, as a matter of principle, viz the modulatory effect could be different for individual target neurons. Diffusive modulatory control is not target specific on the level of individual neurons, being a volume effect.

The influence of neuromodulators in the brain seems to be predominantly diffusive in above sense [28]. Neuromodulators can be compared to hormones on a functional level, which also act diffusively. Hormones are synthesized in certain glands, dispensed throughout the body via the blood system and act as diffusive chemical messengers. Both hormones and neuromodulators may have lasting as well as phasic effects on their respective targets. Stress hormones change the actual working stage of the body into a fight-or-flight stance, growth hormones fulfil their task on the other side over the course of months and years.

Cognitive System Theory

Let us now consider the overall picture. In Fig. 2, the functional interdependencies between cognitive processes, environment and emotional control are illustrated. These interdependencies hold both for real-world cognitive systems, like the human cognitive system, as well as for

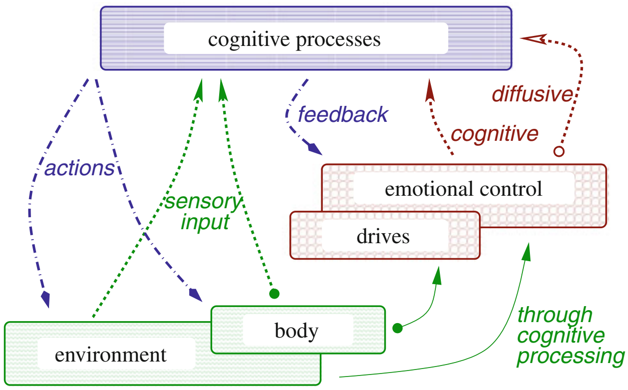

Fig. 2 Functional relation between the cognitive processes, environment and emotional control. The biological support unit (the body) and the wetware (the brain) are functionally part of the environment. The motivational drives are traditionally divided into the primary drives and higher emotional control, the former responsible for securing daily survival, the latter for optimizing life-long Darwinian fitness. The paradigms of embodied cognition/emotion state that the proprioceptual sensory input from the body (*lines with filled arrows and circles*) to the cognitive processes/emotional control is essential for cognition/emotions. The paradigm of diffusive emotional control states that emotions are functionally dependent on diffusive modulatory control (*line with open arrow and circle*)

organismic artificial intelligences. We start the discussion by considering the individual components.

- **Cognitive processes** All standard conscious and unconscious neural activities, like neural firing and learning via synaptic plasticities, belong to the class of cognitive processes.
- **Environment** Notably, here is the circumstance, that the support unit of the cognitive system, the body, belongs to the environment. It can be acted upon, as any other part of the environment, and the cognitive system can obtain sensory information about it, either via the normal sensory organs or proprioceptionally. The body is however a very special part of the environment and plays a central role in the notion of embodiment, as discussed further below. An organismic cognitive system dies by definition, whenever the support unit ceases to be operational.
- **Emotional control** The emotional control plays a central role in behavioral control, see section “Neutral Versus Emotional Control”. It is only then distinct from cognitive information processing when a diffusive modulatory influence on the cognitive processes is present. Otherwise, one may subsume the emotional processes under the cognitive processes.

Note, that most models for synthetic emotions consider emotional drives to be state variables interacting with other state variables, like neural activity levels, cognitively, e.g. via direct synaptic links [18, 32]. In these models the emotional states typically have global effects and are therefore, to a certain extend, special state variables. They could be subsumed, nevertheless, under cognitive information processing, having analogous functionalities.

Cognitive System Paradigms

In Fig. 2, the dominant interactions between the constituent components of cognitive system and environment are illustrated. One needs to remember however that environment, emotional control and cognitive processing have all their own intrinsic and autonomous dynamical processes. This state of affairs is self evident for the case of the environment, which is generally only weakly and locally affected by the actions of the cognitive system. But also the cognitive processes themselves, viz the neural brain activity, have strong and essential autonomous components [29–31]. The brain is indeed not just a glorified input–output mapper, driven by the sensory data input stream, but a self-sustained dynamical system of its own.

There are contrasting views with respect to the overall importance of the various interactions illustrated in Fig. 2, for a full fledged cognitive system. Disregarding many interesting details, these different views can be stereotyped via their paradigmatic assumptions.

- **Embodied cognition** The brain receives sensory information both via sensory organs like eyes and ears, as well as proprioceptual information from the own body. The paradigm of embodied cognition states, among other things, that the proprioceptual sensory input is not only helpful, but an essential part of cognition [33, 34].
- **Embodied emotions** The emotional control system receives information both about the environment, preprocessed cognitively, as well as direct proprioceptual input from the body. The paradigm of embodied emotions states that the proprioceptual information is an essential part of emotions in general and of emotion experience in particular [35, 36].
- **Diffusive emotional control** The emotional control system might influence the cognitive processes both directly or via modulatory processes, as described in section “Diffusive, Modulatory and Cognitive Control”, with the modulatory processes being diffusive volume effects. The paradigm of diffusive emotional control states, that a key functionality of natural and synthetic emotions involves diffusive control [37], viz that cognitive emotional control alone may only mimic certain secondary features of emotional control, but not reproduce the core functionalities.

The term “cognitive system” is widely used in a range of contexts, sometimes for large-scale cognitive architectures, more often however for specialized algorithms suitable for solving certain well defined tasks. Here we use the term cognitive system as a synonym for "organismic cognitive system" [5, 6], as corresponding to a full-fledged synthetic or real-world cognitive system, like the human cognitive system. The above list of paradigmatic assumptions for cognitive systems is not meant to be exhaustive, many other possible architectures have been proposed. We have focused here, from the viewpoint of dynamical systems theory, on working principles important for organismic cognitive systems.

The concept of diffusive emotional control, which has its groundings in neurobiological observations, constitutes a mathematically well-defined proposal of how to implement synthetic emotions. Both emotional control and homeostatic regulative processes involve modulatory control via diffusive volume processes. Indeed, as mentioned in the introduction, emotional control is evolutionary-wise an offspring of homeostatic control. What is then the difference between normal or neutral and emotional diffusive control? This riddle, which is the subject of section "Neutral Versus Emotional Control", is not resolved by the paradigm of diffusive emotional control alone.

Cognitive Feedback

We conclude the overall assessment of an organismic cognitive system with the feedback influence of the cognitive processes onto the emotional control, compare Fig. 2.

Cognition and emotions are deeply intertwined [24, 39], and it is clear that cognitive processing influences the emotional control via direct feedback loops. It is possible, to give an example, to lay relaxed on a couch with closed eyes, meditating about the happenings of the last days and experiencing an emotional roller coaster. Emotions can be triggered both by environmental stimuli as well as by cognitive processes.

The emotional control system has, in any case, no sensory organs of its own. The emotional system cannot obtain direct information about the environment, all sensory input arriving to the emotional control is cognitively preprocessed, compare Fig. 2. It is however presently a matter of debate exactly to which cognitive information the emotional control system has access to. It has been argued [38], to give an example, that the dopamine neurons in the substantia nigra receive visual information through the superior colliculus, which is specialized in localizing changes of luminance in the visual field, directing, beside others, saccadic eye movements. In this case, the dopaminergic neurons in the substantia nigra would have access only to a very limited and specialized sector of cognitive information.

The fundamental drives like hunger and pain are less influenced by cognitive feedback and more driven by signaling from the body. The distinction between the fundamental drives and the higher emotional control can be made precise, when identifying the drives with the "primary survival parameters" [37], viz with the set of parameters regulating the survival of the body. In this interpretation, the level of blood sugar, the heart beating frequency and the level of pain, to mention a few, need to be kept homeostatically in a certain range by the cognitive system for the support unit to retain operationability. We die when our blood sugar level raises above, or falls below, a certain critical level.

Neutral Versus Emotional Control

Our discussion has led us so far to two points:

– Substantial support from neurobiology indicates that the neuromodulatory system acts via diffusive volume processes. The effect of a neuromodulator on the neurons in the target area is modulatory and not cognitive. The neuromodulators do not affect the actual firing states or the membrane potentials directly, modulating the internal parameters like firing thresholds, learning rates, etc. With emotions being linked to the concurrent release of neuromodulators, these results have important consequence for models of synthetic emotions. Models of emotions involving cognitive emotional control, instead of diffusive control, may be useful for applications but will not lead in the end to 'true synthetic emotions'.
– The neuromodulatory system is part of the web of homeostatic regulations. The vast majority of homeostatic processes occurring in our bodies and in the brain are however neutral, not evoking emotional experiences. Which key functionalities then differentiate neutral from emotional control? This is the question we are addressing in the present section.

A word of caution. We will propose here a functional difference between neutral and emotional homeostatic control, based on theoretical as well as on neurobiological considerations, a proposal which is implementable and such also falsifiable. Whether or not functional properties of emotional control alone suffice for an explanation of emotional experiences is presently however unclear. We start our discussion by considering the motivational problem.

The Motivational Problem

Any organismic cognitive system has to take actions. The question is then which actions and for which purposes. We propose there that this motivational problem can be classified, cum grano salis, into two separate time windows.

- **Day-to-day survival** The task to keep the body healthy on a daily basis is job of the primary drives, which take their input from survival parameters, see section “Cognitive Feedback” and Fig. 2. The survival parameters, like the heart beating frequency, signal proprioceptually the status of the support unit to the cognitive system. The resulting primary drives, like hunger and reproduction, constitute the only set of motivational drives for primitive organismic cognitive systems.
- **Life-long Darwinian fitness** The survival probability, over the lifespan of an individual, and the overall number of offsprings can benefit from complex behavioral strategies which transcend the requirements for day-to-day survival. Optimizing life-long Darwinian fitness is a primary task of emotional control.

Two examples: Many animals will engage in social activities when immediate survival is not at stake, improving such lifelong survivability (securing the protection of the kins) and Darwinian fitness (increasing the chances of obtaining a mate). Many humans will engage in explorative activities when being bored, viz when the operational status of mind and body is close to optimality. General explorative behaviour, viz exploration without an explicit goal, may indeed potentially increase longer-term fitness, e.g. when finding a shelter for the next winter, or when discovering additional nutriment sources for possible times of hardness.

The existence of deep interrelations between emotional control, decision making and behavior is well established [40–42]. Indeed the notion of empathy, the possibility to understand deeply the feelings of other persons is important in social contexts since empathic understanding allows to predict the likely future course of actions of your counterpart [44]. The mere fact that empathy evolved through evolutionary selection therefore directly implies that emotional control constitutes a key player in behavioral control.

Emotions have a twofold functionality for behavioral control. On one side they establish general moods of direct behavioral relevance, like boredom in the example above. Cognitively evaluated plans and targets are, in addition, emotionally weighted, a precondition for decision making in the framework of both short- and long-term planing. Policy making is therefore intrinsically dependent, also for highly developed cognitive systems, on a solid emotional grounding, the biological counterpart to the value function used in the context of reinforcement learning [43].

The here postulated separation of time scales for instincts and emotional control needs to be interpreted non-exclusively. Instincts contribute to the long-term fitness, but only indirectly through a succession of short-term survivals. Emotional control can contribute however directly both to the prospective life-long fitness and to the daily survival rate.

Emotional Control Versus Utility Maximization

One may then wonder [22, 37], which is the advantage of having, in addition to the primary drives like hunger and reproduction, an additional layer of motivational drives, the emotional control. A mainstream hypothesis in artificial intelligence research assumes that high-level synthetic cognitive systems having life-long utility maximization as their sole motivational drive [45], may eventually be constructed. The artificial cognitive system would then, in this view, take into consideration all facts known about the environment, make a large computational effort, and maximize directly a preset utility function.

Emotional control in mammals works however indirectly. Emotions do in general not direct the behavior towards a straight-forward utility maximization, e.g. when exploring the environment when nothing else is to do. We believe that general, emotionally induced, behavioral strategies are an essential part of behavioral control in the face of complex environments. Any real-world cognitive system is confronted with a shortage of three types of resources:

- information about the environment is (extremely) limited,
- the computational resources (of the brain) finite and
- the time available for taking decisions (very) short.

The scarceness of theses three resources makes it impossible for an organismic cognitive system to optimize directly Darwinian fitness over longer time spans, like weeks, months and years. Emotionally regulated behavior has proven itself, through selection and evolution, to be a feasible route to achieve high levels of Darwinian fitness when only modest resources (information, computational capabilities and time) are available.

Emotional control achieves computational effectiveness by providing general evaluation benchmarks, making situation-specific evaluations, which are computationally expensive and very time consuming, feasable. Consider a paleolithic tribe wandering around in search for a place to settle. They will likely direct their pace towards places looking nice, like a savannah interspersed with patches of forest, or a small stream with sheltering rocks. This emotional valuation, ‘this place looks welcoming’, is based on a very small subset of potentially available information. It can be performed very fast and is computationally affordable, having a substantial influence on the longer-term Darwinian fitness of the tribe-members.

A utility maximization procedure would correspond in this situation, on the other side, to a realistic assessment of the perspectives: how many heads of game will we be able to hunt here during the next few months? How many roots and vegetables will we be able to gather, which is the likelihood of a forest-fire? and so on. A rigorous utility maximization would clearly need a substantial investment of time and resources for data acquisition and evaluation, a luxury not available in most situations.

Homeostatic Interactions

Emotions correspond to homeostasis at the behavioral level [46]. Is there then a functional difference, which makes certain homeostatic regulation by neuromodulators 'emotional', in contrast to automatic homeostatic processes, which we may term 'neutral'? A vast body of clinical data shows that emotions and the organization of behavior through motivational drives are intrinsically related [16, 42, 47, 48].

Highly developed cognitive systems need to acquire adequate response strategies for given states of emotional arousal. When angry, to give an example, one has to find out which actions are suitable for reducing this unpleasant level of arousal. These response actions are generally not genetically predetermined, since quite disparate environmental situations may lead to increased levels of angriness: shooing away an annoying fly is an utterly different action than settling a quarrel with a spouse.

Response strategies are acquired algorithmically via reinforcement or temporal-difference learning [43]. These learning processes make use of reward signals and a given behavioral response will be enhanced or suppressed for positive and negative reward signals, respectively, a well-known candidate for a reward signal in the brain being dopamine [28, 49].

> Emotional diffusive control is therefore characterized by a coupling of the regulative event to the generation of reward signals for subsequent reinforcement learning processes.

It has been proposed [37], that this coupling is the characteristic hallmark of emotional control, differentiating it to neural control processes.

Which are the conditions for the generation of the reward signals coupled to emotional control? Let us come back to above example. If we are angry, we will generally try to perform actions with the intent of reducing our level of arousal. Angriness is reduced when this goal is achieved, and a positive mood follows, viz a positive reward signal has been generated, reinforcing the precedent behavior. The generation of reward signals is hence coupled to the arousal level of the emotional control processes. The distinguishing attribute of emotional control is therefore a genetically predetermined activation or arousal level. Deviations from this preferred range of activation will lead to positive or negative reinforcement signals.

We conclude this section with a note of caveat. The functional characterization of emotional control given above makes no statement regarding the preconditions necessary for emotional experiences. Introspectively, the qualia of emotional experiences is qualitatively different from cognitive reasoning and thinking. It is presently unclear which attributes of the emotional circuits are essential for emotional experiences. Embodiment may play a crucial role in this respect. Emotions standardly influence the status of the body via the release of hormones, like adrenaline, and we are in part able to sense proprioceptually the resulting bodily effects. In this view, the experience of emotions would correspond to proprioceptual perception [50].

Conclusions

Discussing the functional role of emotional control, we have identified two core properties:

- Emotional control via appropriate neuromodulators corresponds to diffusive modulation of the neural activity and not to direct cognitive control.
- Emotional control is part of the homeostatic control system with the difference being that the level of emotional arousal is linked to the release of positive or negative reinforcement learning signals.

These findings, which are based on neurobiological and clinical observations, have two implications. On one side, they specify mathematically well characterized functional features of diffusive emotional control and are therefore implementable for synthetic cognitive systems. They are, on the other hand, quite general statements and a myriad of interesting and important additional details are needed in order to obtain a deeper understanding of emotional control. In this context, we have presented a hypothesis regarding the benefit of emotional control for the Darwinian fitness of an organismic cognitive system, arguing that it contributes to the optimization of both life-long fitness and daily survival, with the latter being the domain of motivational control through instincts.

We have emphasized in this review the functional differences between emotional control and cognitive computation. On the other side, we have also pointed out that both cognition and emotional control are two indispensable components of any full-fledged organismic cognitive system. The motivational problem cannot be solved by cognition alone, any highly developed cognitive system would remain goal-less stranded and disoriented without solid and well developed emotional groundings.

References

1. Rolls ET. Emotion explained. Oxford: Oxford University Press; 2005.
2. Damasio AR. Descartes error: emotion, reason and the human brain. USA: Putnam Pub Group; 1994.
3. Damasio AR. The feeling of what happens: body and emotion in the making of consciousness. San Diego: Harcourt; 1999.
4. Gros C. Complex and adaptive dynamical systems, a primer. Berlin: Springer; 2008.
5. Froese T, Ziemke T. Enactive artificial intelligence: investigating the systemic organization of life and mind. Artif Intell. 2009;173:466–500.
6. Ziemke T, Sharkey N. A stroll through the worlds of robots and animals. Semiotica. 2001;134:701–46.
7. Barrett LF, Mesquita B, Ochsner KN, Gross JJ. The experience of emotion. Annu Rev Psychol. 2007;58:373–03.
8. LeDoux JE. Emotion circuits in the brain. Annu Rev Neurosci. 2000;23:155–84.
9. Aron A, Fisher H, Mashek DJ, Strong G, Li H, Brown LL. Reward, motivation, and emotion systems associated with early-stage intense romantic love. J Neurophysiol. 2005;94:327–37.
10. Blakemore SJ, Winston J, Frith U. Social cognitive neuroscience: where are we heading? Trends Cogn Sci. 2004;5216–222.
11. Lieberman MD. Social cognitive neuroscience: a review of core processes. Annu Rev Psychol. 2007;58:259–89.
12. Adolphs R. Cognitive neuroscience of human social behaviour. Nat Rev Neurosci. 2003;4:165–78.
13. Breazeal C. Emotion and sociable humanoid robots. Int J Hum Comput Stud. 2003;59:119–55.
14. Duffy BR. Anthropomorphism and the social robot. Rob Auton Syst. 2003;42:177–90.
15. Fong T, Nourbakhsh I, Dautenhahn K. A survey of socially interactive robots. Rob Auton Syst. 2003;42:143–66.
16. Arbib MA, Fellous JM. Emotions: from brain to robot. Trends Cogn Sci. 2004;8:554–61.
17. Ziemke T, Lowe R. On the role of emotion in embodied cognitive architectures: from organisms to robots. Cognit Comput. 2009;1:104–17.
18. Vallverdu J, Casacuberta D. editors. Handbook of research on synthetic emotions and sociable robotics: new applications in affective computing and artificial intelligence. Hershey: IGI-Global; 2009.
19. Marder E, Goaillard JM. Variability, compensation and homeostasis in neuron and network function. Nat Rev Neurosci. 2006;7:563–74.
20. Bak LK, Schousboe A, Waagepetersen HS. The glutamate/GABA-glutamine cycle: aspects of transport, neurotransmitter homeostasis and ammonia transfer. J Neurochem. 2006;98:641.
21. Giocomo LM, Hasselmo ME. Neuromodulation by glutamate and acetylcholine can change circuit dynamics by regulating the relative influence of afferent input and excitatory feedback. Mol Neurobiol. 2007;36:184–200.
22. Krichmar JL. The neuromodulatory system: a framework for survival and adaptive behavior in a challenging world. Adapt Behav. 2008;16:385–99.
23. Burgdorf J, Panksepp J. The neurobiology of positive emotions. Neurosci Biobehav Rev. 2006;30:173–87.
24. Pessoa L. On the relationship between emotion and cognition. Nat Rev Neurosci. 2008;9:148–58.
25. Fellous J-M. The neuromodulatory basis of emotion. Neuroscientist 1999;5:283–94.
26. Grey JR. Integration of Emotion and Cognitive Control. Curr Dir Psychol Sci. 2004;13:46–8.
27. Ochsner KN, Gross JJ. The cognitive control of emotions. Trends Cogn Sci. 2005;9:241–49.
28. Arbuthnott GW, Wickens J. Space, time and dopamine. Trends Neurosci. 2007;30:62–9.
29. Gros C. Self-sustained thought processes in a dense associative network. Springer Lecture Notes Artif Intell. 2005;3698:366–79.
30. Gros C. Neural networks with transient state dynamics. New J Phys. 2007;9:109.
31. Gros C. Cognitive computation with autonomously active neural networks: an emerging field. Cognit Comput. 2009;1:77–99.
32. Cañamero LD. Emotion understanding from the perspective of autonomous robots research. Neural Netw. 2005;18:445–55.
33. Wilson M. Six Views of Embodied Cognition. Psychon Bull Rev. 2002;9:625–36.
34. Anderson ML. Embodied cognition: a field guide. Artif Intell. 2003;149:91–130.
35. Niedenthal PM. Embodying emotion. Science 2007;316:1002.
36. Panksepp J. On the embodied neural nature of core emotional affects. J Conscious Stud. 2005;12:158–84.
37. Gros C. Emotions, diffusive emotional control and the motivational problem for autonomous cognitive systems. In Vallverdu J, Casacuberta D, editors. Handbook of research on synthetic emotions and sociable robotics: new applications in affective computing and artificial intelligence. Hershey: IGI-Global; 2009.
38. Redgrave P, Gurney K. The short-latency dopamine signal: a role in discovering novel actions? Nat Rev Neurosci. 2006;7:967–75.
39. Phelps EA. Emotion and cognition: insights from studies of the human amygdala. Annu Rev Psychol. 2006;52:27–53.
40. Dolan RJ. Emotion, cognition, and behavior. Science 2002;298:1191–94.
41. Panksepp J. At the interface of the affective, behavioral, and cognitive neurosciences: decoding the emotional feelings of the brain. Brain Cogn. 2003;52:4–14.
42. Coricelli G, Dolan RJ, Sirigu A. Brain, emotion and decision making: the paradigmatic example of regret. Trends Cogn Sci. 2007;11:258–65.
43. Sutton RS, Barto AG. Reinforcement learning: an introduction. Cambridge: MIT Press; 1998.
44. De Vignemont F, Singer T. The empathic brain: how, when and why? Trends Cogn Sci. 2006;10:435–41.
45. Hutter M. Universal artificial intelligence: sequential decisions based on algorithmic probability. Berlin: Springer; 2005.
46. Craig AD. A new view of pain as a homeostatic emotion. Trends Neurosci. 2003;26:303–07.
47. Bechara A, Damasio H, Damasio AR. Emotion, decision making and the orbitofrontal cortex. Cereb Cortex. 2000;10:295–07.
48. Naqvi N, Shiv B, Bechara A. The role of emotion in decision making: a cognitive neuroscience perspective. Curr Dir Psychol Sci. 2006;15:260–64.
49. Doya K. What are the computations of the cerebellum, the basal ganglia and the cerebral cortex? Neural Netw. 1999;12:961–74.
50. Prinz JJ. Is emotion a form of perception? Can J Philos. 2006;32:137–60.