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A systems approach to appraisal mechanisms in emotion

David Sander*, Didier Grandjean, Klaus R. Scherer

Geneva Emotion Research Group, Department of Psychology, University of Geneva, 40, Bd. du Pont d'Arve, CH-1205, Geneva, Switzerland

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Abstract

While artificial neural networks are regularly employed in modeling the perception of facial and vocal emotion expression as well as in automatic expression decoding by artificial agents, this approach is yet to be extended to the modeling of emotion elicitation and differentiation. In part, this may be due to the dominance of discrete and dimensional emotion models, which have not encouraged computational modeling. This situation has changed with the advent of appraisal theories of emotion and a number of attempts to develop rule-based models can be found in the literature. However, most of these models operate at a high level of conceptual abstraction and rarely include the underlying neural architecture. In this contribution, an appraisal-based emotion theory, the Component Process Model (CPM), is described that seems particularly suited to modeling with the help of artificial neural network approaches. This is due to its high degree of specificity in postulating underlying mechanisms including efferent physiological and behavioral manifestations as well as to the possibility of linking the theoretical assumptions to underlying neural architectures and dynamic processes. This paper provides a brief overview of the model, suggests constraints imposed by neural circuits, and provides examples on how the temporal unfolding of emotion can be conceptualized and experimentally tested. In addition, it is shown that the specific characteristics of emotion episodes can be profitably explored with the help of non-linear dynamic systems theory.

Despite its remarkable development over the past 30 years, neural network modeling has largely neglected emotion, despite some valiant efforts by early pioneers. Thus, McClelland (1997) and Rumelhart (1997) have suggested that a standard connectionist model of the relation between mind and brain could be elaborated on to explain certain affective phenomena. Armony and LeDoux (2000) have described interactions between fear mechanisms and cognitive systems using parallel connectionist modeling of the mechanisms presumed to underlie the results of their neurobiological rat studies. Psychologists interested in understanding the cognitive and attentional bases of affective disorders such as anxiety neurosis, depression, and emotional distress have equally turned to connectionist modeling of the presumed neural bases (Matthews, Derryberry, & Siegle, 2000; Matthews & Harley, 1996; Williams & Oaksford, 1992). Researchers interested in the perception of facial and vocal emotion expression as well as in automatic expression decoding also use artificial neural networks in order to model the recognition process (see Fragopanagos & Taylor, in press). However, despite these important inputs, so far there has been little effort to produce computational models of emotional processes using neural network approaches. This may be due, at least in part, to the fact that the emotion models that have dominated the field over the past 30 years are not particularly well suited to this type of computational modeling. Discrete emotion theory (Ekman, 1972; Izard, 1971; Tomkins, 1962/3) has generally considered the emotions as specific response patterns to highly prototypical eliciting situations, requiring a minimum of cognitive computation, and presuming a large amount of genetic pre-programming of the neuro-motor response programs. Dimensional theories of affect (e.g. Lang, Greenwald, Bradley, & Hamm, 1993; Russell, 1980; Wundt, 1905) are mostly focused on what Russell (2003) calls 'core affect', i.e. the crude location of subjective feeling in a two-dimensional valence-by-activation space, worrying little about the underlying cognitive mechanisms and their relationships to efferent responses.

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* Corresponding author. Tel.: +41 22 379 92 12; fax: +41 22 379 92 19.
E-mail addresses: david.sander@pse.unige.ch (D. Sander), didier.grandjean@pse.unige.ch (D. Grandjean), klaus.scherer@pse.unige.ch (K.R. Scherer).

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Understandably, these models have provided little impetus for the kind of computational modeling stemming from a cognitive neuroscience approach.

The study of emotion has received fresh impetus from componential approaches based on the notion that emotional processes are elicited and dynamically patterned as the individual continuously and recursively appraises objects, behaviors, events, and situations with respect to their effect on his/her values, goals, and general well-being. Importantly, this approach highlights the role of different forms of cognition in the shaping of emotion as well as in recursive effects of emotion on cognition. Such componential models of emotion (Ellsworth & Scherer, 2003; Scherer, Schorr, & Johnstone, 2001) successfully challenge classic conceptualizations of emotion such as discrete emotion theories or dimensional theories (as they provide a theoretical framework that can explain both the elicitation and the multimodal reaction patterning in a dynamic perspective and account for the extraordinary changeability and the high degree of qualitative differentiation of emotional experience). In addition, componential theorists are starting to identify the brain circuits and neural dynamics that subserve appraisal processes and drive peripheral response patterns (Grandjean & Scherer, in preparation; Sander, Grafman, & Zalla, 2003; Sander & Scherer, in press) and to encourage the development of computational models of component emotion processes (Frijda & Swagerman, 1987; Scherer, 1993; Wehrle & Scherer, 2001; see also Gratch & Marsella, 2004; Staller & Petta, 1998, 2001).

In this paper, we first present an overview of a specific componential theory, the component process model of emotion (CPM; see Scherer, 1984a, 1984b, 1986, 1993a, 2001), highlighting the appraisal-driven synchronization of multi-modal response patterns and their integration into subjective feeling, with consciousness as an emergent quality. Second, we argue that a cognitive neuroscience approach to appraisal processes may help to constrain models of emotion; in particular, this approach is critical for understanding how neural networks sub-serve the cognitive processes that drive the emotional response. With the goal of providing evidence for the usefulness of the approach (rather than of being comprehensive), we discuss three fundamental aspects of the *appraising brain*. In the first subsection, we discuss how the investigation of the *domain of processing* of specialized neural networks can constitute evidence for the existence of specific appraisals. In the second subsection, we discuss how the investigation of the temporal dynamics of neural networks can constitute evidence for the sequential temporal unfolding of appraisals. In the third subsection, we discuss how the investigation of dissociable neural networks may constitute evidence for the existence of different *levels of processing* in appraisal. Third, with respect to computational modeling of the underlying processes, we propose a dynamic nonlinear systems approach as most appropriate to capture the specificity of emotion phenomena. We argue for the advantages of neural network architectures to model sequential appraisal-driven response patterning, based on parallel neuro-cognitive processing and fuzzy activation propagation, and to represent the extraordinary richness and subtlety of the subjectively experienced quality of emotion (the philosophers' *qualia*).

1. The component process model

Emotion is a phylogenetically continuous mechanism allowing increasingly flexible adaptation to environmental contingencies by decoupling stimulus and response and thus creating a latency time for response optimization (Scherer, 1979, 1984, 1987). Emotion is considered as a theoretical construct that consists of five components corresponding to five distinctive functions (see Table 1 for a list of the functions, the systems that sub-serve them and the respective emotion components). As these components are part of the psychobiological endowment of higher organisms, one might ask how emotional states are to be distinguished from non-emotional states in the flow of experience of an organism. In the framework of the component process model, emotion is defined as *an episode of interrelated, synchronized changes in the states of all or most of the five organismic subsystems in response to the evaluation of an external or internal stimulus event as relevant to major concerns of the organism*. Concretely, the term 'emotion' is reserved for those periods of time during which several organismic subsystems are coupled or synchronized to produce an adaptive reaction to an event that is considered as central to the individual's well-being.

Table 1
Relationships between the functions and components of emotion, and the organismic subsystems that subserve them

Emotion function	Emotion component	Organismic subsystem (and major substrata)
Evaluation of objects and events	Cognitive component	Information processing (CNS)
System regulation	Peripheral efference component	Support (CNS, NES, ANS)
Preparation and direction of action	Motivational component	Executive (CNS)
Communication of reaction and behavioral intention	Motor expression component	Action (SNS)
Monitoring of internal state and organism-environment interaction	Subjective feeling component	Monitor (CNS)

CNS, central nervous system; NES, neuro-endocrine system; ANS, autonomic nervous system; SNS, somatic nervous system. The organismic subsystems are theoretically postulated functional units or networks.

The major features of this definition are discussed in greater detail below.

1.1. The sequential check theory of emotion differentiation

How does the emotion process get started and become differentiated? Many philosophers implicitly evoked an evaluation of the personal significance of events as central antecedents of emotional experience (Gardiner, Clark-Metcalf, & Beebe-Center, 1937/1980). However, it was not before Arnold (1960) and Lazarus (1966) that the term *appraisal* was used in this context. Based on the work of these pioneers, modern appraisal theories evolved, first independently of each other, but rapidly showing a high degree of convergence (see Scherer, 1999a, 1999b; Schorr, 2001, for systematic and historical overviews).

The central contribution of modern appraisal theories is to specify a standard set of criteria, dimensions, or checks that are presumed to underlie the emotion-constituent appraisal process. In other words, as an event unfolds, the individual concerned would evaluate its significance on a number of criteria such as pertinence of the consequences to one's well-being, conduciveness or obstructiveness for one's plans and goals, and the ability to cope with such consequences (see Roseman & Smith, 2001; Scherer, 1999a, 1999b). In Scherer's component process model, described here, these criteria are called *stimulus evaluation checks* (SECs).

1.2. The nature of the stimulus evaluation checks

The SECs postulated in the most recent version of the model (Scherer, 2001) are organized in terms of four *appraisal objectives* concerning the major *types or classes of information* that an organism needs to adaptively react to a salient event: (1) How relevant is this event for me? Does it directly affect me or my social reference group? (*relevance*); (2) What are the implications or consequences of this event and how do these affect my well-being and my immediate or long-term goals? (*implications*); (3) How well can I cope with or adjust to these consequences? (*coping potential*); (4) What is the significance of this event with respect to my self-concept and to social norms and values (*normative significance*).

These checks will be briefly summarized below. It should be noted that the presumed outcomes of all SECs are highly subjective, based on the individual's inference (which may not faithfully represent the objective characteristics of an event; see Perrez & Reicherts, 1995). Thus, individual differences (see van Reekum & Scherer, 1997), transitory motivational states or moods (Forgas, 1991), and cultural values, group pressures, and the like can strongly influence the appraisal outcomes (see Manstead & Fischer, 2001; Mesquita & Ellsworth, 2001; Mesquita, Frijda, & Scherer, 1997; Scherer, 1997a, 1997b).

(1) *Relevance detection*. Organisms constantly scan their external and internal environment for the occurrence of events (or the lack of expected ones) requiring deployment of attention, further information processing, and possibly adaptive reaction. Three checks are involved:

(a) *Novelty check*. Any novel stimulus requires attention and demands further processing. We propose to differentiate three features of novelty: (i) *suddenness* or *abruptness* of onset (Tulving & Kroll, 1995), often coupled with high stimulation intensity, producing an orientation response (Siddle & Lipp, 1997); (ii) *familiarity* with the object or event (Tulving et al., 1996), generally based on schema matching; and (iii) *predictability*, as based on past observations of regularities and probabilities for specific events.

(b) *Intrinsic pleasantness check*. On a very low level of processing (see below), the organism evaluates, with the help of genetically fixed schemata or overlearned associations, whether a stimulus event is likely to result in pleasure or pain (in the widest sense). The term *intrinsic* refers to the fact that the evaluation is produced by a *feature of the stimulus* and is thus independent of the momentary preferences or goal states of the organism (see Table 3 in Scherer, 1988 for the distinction from the positive evaluation of stimuli that help reach goals or satisfy needs). A pleasantness encourages approach, whereas unpleasantness leads to withdrawal or avoidance (e.g. a defense response; Vila & Fernandez, 1989).

(c) *Goal/need relevance check*. What is the relevance, pertinence, or importance of an event or situation for one's goals/needs? Relevance varies continuously from low to high, depending on the number of needs, goals, or values that are affected by the event and/or their relative status in the hierarchy of priorities. For example, an event is much more relevant if it threatens one's livelihood or even one's survival than if it just endangers one's need to eat dinner. This is the most complex aspect of relevance detection and rather badly understood at the moment. It requires checking (and weighting) potential consequences of an event against a large array of expectations (*Sollwerte*) generated by different types of motivational constructs (Austin & Vancouver, 1996).

(2) *Implication assessment.* The potential consequences of an event are difficult to predict. To allow at least approximate estimation of implications, consequences, and future developments, one needs to know more about the event and its causation. Therefore, the individual has to infer and estimate a number of important parameters. The following five checks seem to be minimally required:

(a) *Causal attribution check*. The most important information concerns the cause of the event, in particular agent and intentionality. In other words, who did it and why? The attribution processes are quite complex (see Weiner, 1985, for some of the factors involved). Obviously, the evaluation of the further evolution of the situation, in particular the probability of the outcomes and one's ability to deal with them, will greatly depend on the result of the attribution of agency and intention. For example, if a flowerpot hits my head, much depends on the propelling force and its underlying teleology.

(b) *Outcome probability check*. The individual needs to assess the likelihood or certainty with which certain consequences are to be expected. What is the probability that another flowerpot will nearly miss my head? This check is of particular importance in the case of *signal events* (e.g. a verbal threat) in which both the probability of the signaled event occurring and its consequences are in doubt.

(c) *Discrepancy-from-expectation check*. The situation created by the event can be consistent or discrepant with the individual's expectation concerning that point of time or position in the action sequence leading up to a goal. If my significant other had a tendency to use potted plants to express his/her dissatisfaction, the event should, depending on my behavior, not be that discrepant from what could be expected.

(d) *Goal/need conduciveness check*. The more the behaviors (one's own or that of others) or events facilitate or help goal attainment, the higher the *conduciveness* of an event (see also Oatley & Duncan, 1994). The more that they block a goal-directed behavior sequence, putting goal or need satisfaction out of reach, delaying their attainment, or requiring additional effort (see Srull & Wyer, 1986), the higher their *obstructiveness*, producing frustration. Typically, conduciveness leads to positive emotions and obstructiveness to negative emotions, quite independently of prior expectations or the intrinsic pleasantness of the stimuli concerned (see Scherer, 1988).

(e) *Urgency check*. Adaptive action in response to an event is urgent when high priority goals/needs are endangered, and the organism has to resort to fight or flight, and/or when it is likely that delaying a response will make matters worse. Urgency depends not only on the significance of an event for an organism's goal/need but also on temporal contingencies. Its effect is an immediate increase in action readiness and sympathetic response of the autonomic nervous system (ANS).

(3) *Coping potential determination*. Generally, organisms are not reduced to passively enduring the effects of events that happen to them. By appropriate action, including the solicitation of help from others, organisms can forestall the occurrence of negative events or modify their consequences. Thus, the adaptive nature of emotion requires an assessment of one's coping potential, including the amount of control and power one has to modify the event and its consequences or to successfully adjust to outcomes that cannot be controlled. In the case of the flying flowerpots, this might involve calling one's big brother for help, wearing a protective helmet, or quietly resigning oneself to occasional bumps on the forehead.

Three aspects of coping potential need to be appraised: (a) *control*, the extent to which an event or its outcomes can be influenced or controlled by natural agents (i.e. people or animals). If the flowerpots have been set in motion by a hurricane, little control seems possible, whereas a human pot thrower might be more easily controlled, depending on one's (b) *power*, one's ability to change contingencies and outcomes according to one's interests. The sources of power can be manifold—physical strength, money, knowledge, or social attractiveness, among others (see French & Raven, 1959). Unfortunately, the important distinction between control and power criteria is not always made in the literature, where 'controllability' often seems to imply both aspects (see discussions in Garber & Seligman, 1980; Miller, 1981; Öhman, 1987). Finally, (c) the potential for *adjustment*, the ability to live with and accommodate the effects of an event, needs to be checked.

(4) *Normative significance evaluation*. In socially living species, the individual needs to evaluate how the majority of the other group members interpret an action and, especially if the consequences have been caused by one's own behavior, determine the consequences for one's self-esteem. Two subchecks are involved: (a) *Internal standards check*, evaluating the extent to which an action falls short of or exceeds internal standards such as one's personal self-ideal (desirable attributes) or internalized moral code (obligatory conduct); and (b) *External standards check*, evaluating to what extent an action is compatible with the perceived norms or demands of a salient reference group in terms of both desirable and obligatory conduct. For example, a pot-throwing partner might elicit less moral indignation if this type of behavior is a time-honored local custom in the case of marital discord.

1.3. Levels of processing in appraisal

The question of the primacy of affect and cognition has been at the root of a much publicized controversy between Lazarus (1984a, 1984b) and Zajonc (1980, 1984) on cognition–emotion interrelationships (see Schorr, 2001). Leventhal and Scherer (1987) showed that this debate turned around the semantic problem of defining emotion and cognition and suggested the need to specify the details of emotion-constituent information processing, particularly with respect to the level at which processing occurs, i.e. the degree of cortical implication allowing conceptual or propositional processing as compared with sensory-motor or schematic processing.

Table 2 shows examples for the different forms the SECs can take, depending on which of the three levels (Leventhal,

Table 2
Levels of processing for Stimulus Evaluation Checks (adapted from Leventhal & Scherer, 1987, p. 17)

	Novelty	*Pleasantness*	*Goal/need conducive*	*Coping potential*	*Norm/self-compatibility*
(1) Sensory-motor level	Sudden, intense stimulation	Innate preferences/ aversions	Basic needs	Available energy	(Empathic adaptation?)
(2) Schematic level	Familiarity: schemata matching	Learned preferences/ aversions	Acquired needs, motives	Body schemata	Self/social schemata
(3) Conceptual level	Expectations: cause/ effect, probability estimates	Recalled, anticipated, or derived positive-negative evaluations	Conscious goals, plans	Problem solving ability	Self ideal, moral evaluation

1984; see also Buck, 1984) at which they are processed. At the sensory-motor level, the checking mechanisms are mostly genetically determined and the criteria consist of appropriate templates for pattern matching and similar mechanisms (cf. the notion of 'biological preparedness', Öhman, 1987). On the schematic level, the schemata forming the criteria for the SECs are based on social learning processes and much of the processing at this level occur in a fairly automatic fashion, outside of consciousness. On the conceptual level, the SECs are processed primarily via cortical association areas, and involve cultural meaning systems. It is expected that the different levels continuously interact, producing top-down and bottom-up effects (see also Power & Dalgleish, 1997; van Reekum & Scherer, 1997). This fundamental assumption of the component process model obviates much of the criticism concerning the 'cognitivistic bias' of appraisal models of emotion.

It is obvious that the appraisal mechanism as sketched above requires the interaction between many cognitive functions and their underlying neural circuits in the process of comparing the features of stimulus events to stored schemata, representations in memory and self-concept, and expectations and motivational urges of high priority. The appraisal process requires attention deployment to particular stimuli and relies heavily on problem solving or reasoning abilities to compute probabilities of consequences, coping potential, and action alternatives. Fig. 1 shows that there is a bidirectional influence between appraisal and these cognitive functions; for example, minimal attention needs to be given for appraisal to start but a relevance outcome will immediately deploy further attention to the stimulus. Stimulus features are compared with schemata in memory but strongly relevant stimulus features will, following appropriate appraisal, be stored as emotional schemata in memory. Event consequences are compared with current motivational states, but particular appraisal outcomes will change motivation and produce adaptive action tendencies. These bidirectional effects between appraisal and other cognitive functions are

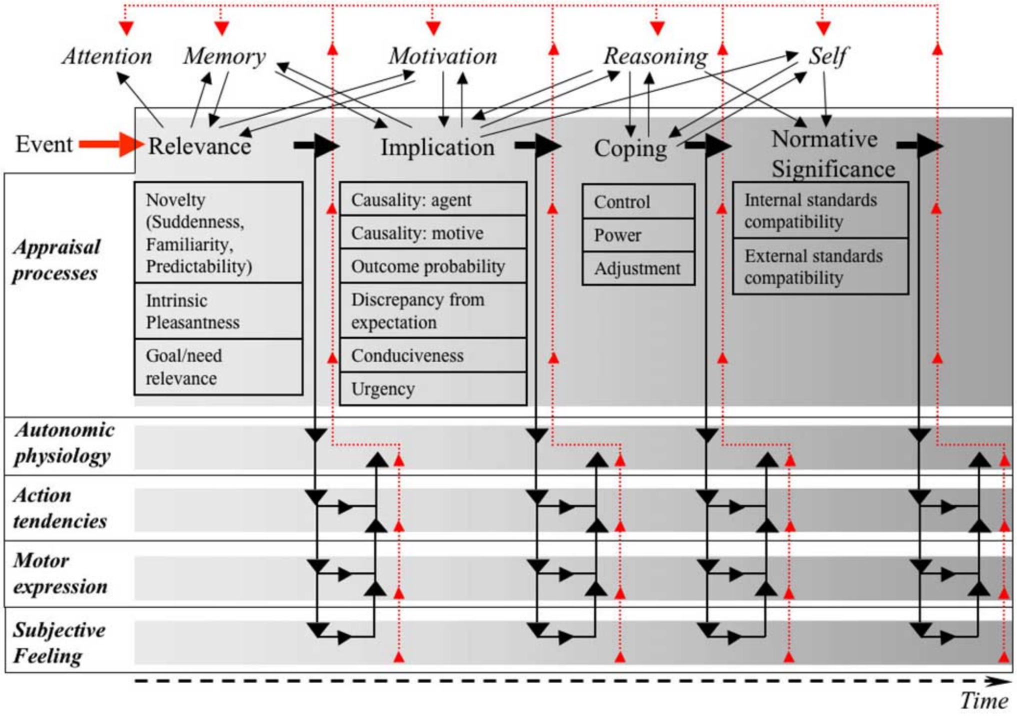

Fig. 1. Comprehensive illustration of the component process model of emotion (see Scherer, 2001).

illustrated by the arrows in the upper part of Fig. 1. The model allows a detailed consideration of the effects of emotional processes on attention, memory, and other cognitive processes. In particular, it suggests a distinction between (i) an effect of particular *appraisal criteria* on other cognitive processes, and (ii) an effect of particular *emotion components* on these cognitive processes. Moreover, *direct* vs. *indirect* types of emotional effects on appraisal criteria can be distinguished. Direct effects consist of the modulation of appraisal criteria by other emotion components. Indirect effects consist of an effect of these components on some cognitive processes that, in turn, can influence appraisal criteria (see Fig. 1). It can be expected that most effects are indirect, e.g. individual emotion components affecting attention and memory.

1.4. The process of appraisal

Appraisal is not a one-shot affair. Organisms constantly scan their environment (and their internal state) to detect, evaluate, and re-evaluate changes. Consequently, the CPM postulates that external or internal event changes maintain a recursive appraisal process until the monitoring subsystem signals termination of or adjustment to the stimulation that originally elicited the appraisal episode.

As shown in Fig. 1, the CPM claims that the SECs are processed in sequence, following a fixed order, consisting of four stages in the appraisal process that corresponds to the appraisal objectives described. This sequence assumption is justified in terms of systems economy and logical dependencies—the results of the earlier SECs need to be processed before later SECs can operate successfully, i.e. yield a conclusive result. Expensive information processing should only occur for those stimuli that are considered relevant for the organism. In consequence, *relevance detection* is considered to be a first selective filter that a stimulus or event needs to pass to merit further processing. Extensive further processing and preparation of behavioral reactions are indicated only if the event actually concerns a goal or need of major importance or when a salient discrepancy with an expected state is detected, suggesting that the *implications* for the organism are assessed next in the sequence. Further, the causes and implications of the event need to be established *before* the organism's *coping potential* can be conclusively determined, as the latter is always evaluated with respect to a specific demand (see Lazarus, 1991, insistence on the *transaction* between individual and event). It can be expected that the level of processing moves up in the course of the sequence, given both the nature of the computation and the likelihood that lower levels have been unable to settle the issue. The *normative significance* of the event, i.e. its consequences for the self and its normative/ moral status, is expected to be appraised last, as it requires comprehensive information about the event and comparison with high-level propositional representation.

This sequence assumption is highly compatible with the assumption of parallel processing. All SECs are expected to be processed simultaneously. However, the essential criterion for the sequence assumption is that point of time at which a particular check achieves *preliminary closure*, i.e. yields a reasonably *definitive* result, one that warrants efferent commands to response modalities, as shown by the bold descending arrows in Fig. 1. The sequence theory postulates that for the reasons outlined above, the result of a prior processing step (or check) must be in before the consecutive step (or check) can produce a conclusive result with efferent consequences. It is indeed feasible to assume that the results of parallel processes for different evaluation criteria will be available at different times, given differential depth of processing (see the discussion of hierarchical processing in Minsky, 1985; Minsky & Papert, 1969/1988).

It can be argued that the microgenetic unfolding of the emotion-antecedent appraisal processes parallels both phylogenetic and ontogenetic development in the differentiation of emotional states. The earlier SECs, particularly the novelty and the intrinsic pleasantness checks, are present in most animals as well as newborn humans, and one can argue that these very low-level processing mechanisms take precedence as part of our hard-wired detection capacities and occur very rapidly after the occurrence of a stimulus event. More complex evaluation mechanisms are successively developed at more advanced levels of phylogenetic and ontogenetic development, with natural selection operating in the direction of more sophisticated information processing ability in phylogenesis and with maturation and learning increasing the individual's cognitive capacity in ontogenesis (see Scherer, 1984a, pp. 313–314; Scherer, Zentner, & Stern, 2004).

1.5. The componential patterning assumption

The CPM suggests that emotion differentiation is the result of the net effect of all subsystem changes brought about by the outcome profile of the SEC sequence. These subsystem changes are theoretically predicted on the basis of a *componential patterning model*. The central assumption of the componential patterning theory is that the different organismic subsystems are highly interdependent and that changes in one subsystem will tend to elicit related changes in other subsystems. As illustrated in Fig. 1, this process is recursive, as one would expect from the neurophysiological evidence for complex feedback and feedforward mechanisms between the subsystems (see neural architecture discussion below).

As shown in Fig. 1, the result of each consecutive check is expected to differentially and cumulatively affect the state of all other subsystems. Here, is an example (from Scherer, 2001, p. 107): "The detection of a novel, unexpected stimulus by the novelty check will produce 1) an orientation response in the support system (e.g. heart rate decrease, skin conductance increase), 2) postural changes in the motivation (or action tendency) system (focusing the sensory reception areas toward the novel stimulus), 3) changes in goal priority assignment in the executive subsystem (attempting to deal with a potential emergency), and 4) alertness and attention changes in the monitor subsystem. When, milliseconds later, the next check, the intrinsic pleasantness check, reaches sufficient closure to determine that the novel stimulus is unpleasant, the efferent effects of this result will again affect the state of all other subsystems and thus modify the changes that have already been produced by the novelty check. For example, an unpleasant evaluation might produce the following changes: 1) a defense response in the support system (e.g. heart rate increase), 2) an avoidance tendency in the executive subsystem, 3) motor behavior to turn the body away from the unpleasant stimulation (thus reducing intake of stimulation in the action system), and 4) a negative subjective feeling in the monitor system. Similarly, all of the following checks will change the states of all other subsystems and will thus further modify the preceding changes.”

In this paper, we cannot discuss the predictions for the effects of specific SEC results on the executive, support, and action systems in the CPM in greater detail. The predictions are based on functional considerations, in terms of both the general functions of the emotion components (see Table 1) and the specific functions of each SEC as discussed above. In particular, specific motivational and behavioral tendencies are expected to be activated in the executive subsystem in order to serve the specific requirements for the adaptive response demanded by a particular SEC result. For socially living species, adaptive responses are required not only in terms of the internal regulation of the organism and motor action for instrumental purposes (organismic functions), but also with respect to interaction and communication with conspecifics (social functions). The model and detailed predictions of response patterns in the central nervous system (CNS), the neuro-endocrine system (NES), the ANS, and the somatic nervous system (SNS) are discussed in greater detail in Scherer (1987); an illustration can be found in Table 3 in Scherer (2001). There is now considerable research evidence, both from our own and other laboratories, for facial expression (see Kaiser & Wehrle, 2001; Wehrle, Kaiser, Schmidt, & Scherer, 2000) and physiological and vocal predictions (Johnstone, van Reekum, & Scherer, 2001; Pecchinenda & Smith, 1996; Smith & Kirby, 2000).

1.6. Multi-modal and temporal integration in the form of subjective feeling

As shown in Table 1, the subjective feeling component has a special role in the emotion process, assumed to serve a monitoring function that is essential for emotional regulation. Any discussion of subjective experience or feeling necessarily involves consciousness, a delicate issue to attack, given the enormous number of publications devoted to the problem and the degree of confusion on the nature and function of consciousness (the two being highly correlated). Recently, Scherer (2004) has presented a CPM account of how feelings integrate the central representation of appraisal-driven response organization in emotion. This proposal is briefly summarized in this section.

It is generally assumed that feelings are conscious phenomena and that the only access to measuring feelings is via verbal report. Unfortunately, this widespread assumption holds only for the visible tip of a huge iceberg. The CPM suggests conceptualizing the problem as shown in Fig. 2, using a Venn diagram in which a set of overlapping circles represent the different aspects of feeling (see also Kaiser & Scherer, 1997). The first circle (A) represents the sheer reflection or representation of changes in all synchronized components in some kind of monitoring structure in the CNS, which receives massive projections from both cortical and sub-cortical CNS structures (including proprioceptive feedback from the periphery). The second circle (B), only partially overlapping with the first, represents that part of the integrated central representation that becomes conscious. This circle corresponds most directly to what is generally called ‘feelings’ or qualia and it feeds the process of controlled regulation, much of which is determined by self-representation and socio-normative constraints. Scherer (in press) has suggested that it is the degree of synchronization of the components (which might in turn be determined by the pertinence of the event as appraised by the organism) that generates awareness.

Unfortunately, the empirical measurement of the processes represented by these two circles is currently not possible. The royal road for obtaining access to subjective experience is to ask the individual for a verbal report of consciously experienced feeling, represented by the third circle (C) in Fig. 2 (a method that is notoriously affected by many biases and artifacts) (Nisbett & Wilson, 1977; Scherer & Ceschi, 2000). This circle overlaps only partially with the circle representing conscious experience (B) because verbal

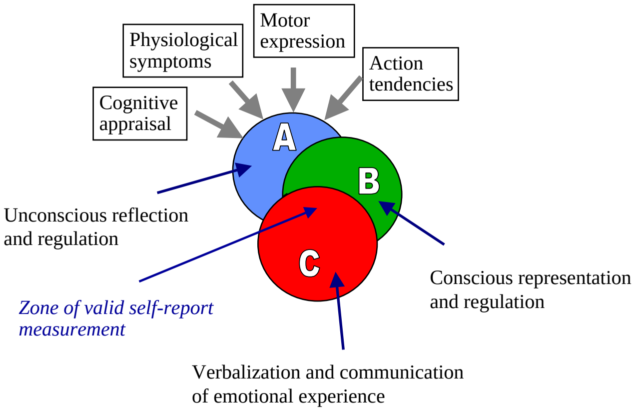

Fig. 2. Venn diagram of the three hypothetical types of central representation of component processes.

report covers only part of what is consciously experienced, due to selective reporting and the constraints of the language categories available.

The account presented above depends in large part on the processes of synchronization and integration within and between components. Within component integration is required because different structures and processes interact in an extremely complex fashion during emotion episodes. Thus, information integration within the cognitive component is required, given the parallel and sequential processing with respect to different evaluation criteria on different levels. Appraisal theorists have generally used profile matching or regression analysis (see review in Scherer, 1999a) to model the integration of the appraisal results, without treating the issue in much detail. Scherer (2004) has suggested using Anderson (1989) integration functions, expected to be strongly determined by the current goals of the organism, to understand the transformation of appraisal results on individual criteria into a coherent implicit response. For example, van Reekum et al. (2004) showed that levels of coping potential have a very different effect upon psychophysiological responses as a function of goal conduciveness because coping ability is of less relevance when things are going according to plan. This could be modeled by Anderson's configuration rule, predicting that the importance of one of the criteria depends on the level of another. Further, work in this area will require a high degree of theoretical specification and research sophistication, including a specification of the transfer functions involved (see Kappas, 2001). It may also turn out that linear functions, as specified in the rules proposed by Anderson (1989), do not provide an appropriate model of the functions in all cases. Scherer (2000) has argued that we may need to adopt non-linear dynamic system analysis as a more appropriate framework for emotion modeling (see Section 4 below) than the classic assumption of linear functions dominating our statistical tool box (e.g. regression analysis).

As shown in Fig. 2, the proprioceptive feedback information from different response components (such as vocal and facial expression or psychophysiological symptoms) must be integrated to yield a coherent representation of feeling qualia. Our knowledge about the integration of proprioceptive cues in the different response components (physiological, facial, vocal, gestural, postural) of the emotion process is extremely limited at the present time, partly because of a flagrant lack of attention to this issue, which is due to most emotion researchers being specialized on only one specific response component. Much basic research will be required to obtain a better understanding of the underlying feedback and integration mechanisms and it would be useful if such research were guided by explicit hypotheses. Neuropsychological findings about the projection and organization of proprioceptive feedback in different domains could provide extremely useful information in this respect, and computational models, especially neural network approaches, might play an important, trail-blazing role.

The CPM suggests that it is the very process of synchronization that constitutes the defining specificity of emotion episodes that elicits and organizes this process of multi-component integration, largely outside of awareness. As Anderson suggested: "What does attain consciousness is often, perhaps always, a result integrated across different sense modalities at preconscious stages" (Anderson, 1989, p. 147).

So far, only the issue of the quality of the subjective experience or feeling and the integration required has been discussed. But of course, the proprioceptive information on the respective amplitude or intensity of the changes in different components must also be integrated toward a common response path. The intensity of feelings has been rarely studied to date (but see Edwards, 1998; Ortony, Clore, & Collins, 1988; Sonnemans & Frijda, 1994) and little is known about the process of integration. The various integration rules proposed by Anderson (1989) are directly applicable here; amplitudes can be averaged or multiplied, or specific configurational rules might apply.

In sum, in trying to understand integration at different points in the emotion episode and the rules likely to underlie this process, the key issue concerns the relative weight given to the different components—appraisal, physiological responses, motor expression, motivation, and action tendencies. A large majority of integration rules are likely to be configurational in nature, implying differential weighting of various response components, probably involving non-linear functions. Here, is an example of configurational weighting: if I am involved in a negotiation, requiring impression management and strategic action, the process of integrating different proprioceptive cues will disproportionately weight the expression component, e.g. facial and vocal behaviors. In contrast, if I am alone, having to decide on a cause of action, the results of event evaluation in the light of current goals and values (the cognitive appraisal component) will be more strongly weighted. Thus, as suggested by Anderson (1989), the integration function, particularly the weighting of different components, may be to a very large extent determined by context and goals. In addition, feeling rules (Hochschild, 1983) may exert strong, normative effects on the weighting of different proprioceptive cues. Thus, feeling can be proactive, in the sense of defining states to be achieved, and elicit processes of cognitive reevaluation and of physiological and expressive regulation, as well as reactively reflect or monitor changes in the different components.

Most important, emotion processes need to be integrated over time. The term 'emotional state' suggests a static, unitary phenomenon rather than a flow of continuously changing component states that constitute emotion episodes. Although we can focus on micro-momentary changes of feeling, we tend to become aware of our feelings in experiential chunks that provide phenomenal unity to a particular feeling quality or qualia. Temporal integration, in the sense of experiential chunking, might be determined by the period during which a certain level of component synchronization persists. Presumably, the same experiential chunks are available as the basis for verbalization even though additional temporal integration may be required as a result of the packaging by narrative or other pragmatic units in speech (see also Kahneman, 2000, for issues of temporal feeling integration).

1.7. Predicting SEC profiles and reaction patterns for modal emotions

Contrary to discrete emotion theories (Ekman, 1984, 1992; Izard, 1977, 1993; Tomkins, 1984), the CPM does not share the assumption of a limited number of innate, hardwired affect programs for basic emotions such as anger, fear, joy, sadness, and disgust. Rather, the emotion process, considered as a continuously fluctuating pattern of change in several organismic subsystems, is expected to yield an extraordinarily large number of different emotions, virtually as many as there are different integrations of appraisal results and consequent response patterns. However, there are some major patterns of adaptation in the life of animate organisms that reflect frequently recurring patterns of environmental evaluation and adaptation results. Thus, Scherer (1984b, 1994) has suggested using the term *modal emotions* for the states resulting from these predominant SEC outcomes that are due to general conditions of life, constraints of social organization, and similarity of innate equipment, generally labeled with a single word.

Since the CPM assumes that emotion differentiation is produced by the results of the SEC sequence, it follows that the latter should also be the key to predicting modal emotions. Table 3 illustrates the predicted profiles of the antecedent SEC result patterns for a few of these modal emotions. For each of the SECs, a graded scale of typical result alternatives is assumed and both the polarity and the grading are used for the predictions. The term ‘open’ indicates that many different results of a particular check are compatible with the occurrence of the respective modal emotion or that the check may be irrelevant for that emotion. The fairly high-frequency of ‘open’ entries can be interpreted as the basis for the emotion variants within a modal emotion family.

Similarly, emotions that are closely related with respect to the basic structure of the antecedent situation may be quite different qualitatively because of grading (or intensity) differences in the SEC results. This is true, for example, for the distinction between hot and cold anger, or between worry and fear. The failure to distinguish between such related states may be the reason for the difficulty of replicating results in research on emotional responses because different investigators may have used similar sounding labels for rather qualitatively different emotional states (see Banse & Scherer, 1996). By combining the predictions for SEC profiles and response patterning, specific response profiles for vocal and facial expression as well as ANS response patterns for these modal emotions can be produced (see Scherer, 1986, 2001, for further details).

So far, only the theoretical framework underlying the CPM has been outlined. Fortunately, there is now much empirical evidence on different parts and predictions of the model. This paper is not the place to describe the experimental evidence from psychology and the reader is referred to recent reviews in separate chapters of a volume on appraisal theories (Scherer et al., 2001; in particular chapters by Johnstone et al.; Kaiser & Wehrle; Roseman & Smith; Scherer). Rather, in what follows, we will discuss how a cognitive neuroscience approach to emotion may lead to critical constraints on the functional organization of appraisal and its efferent effects. As the purpose of this paper is to examine the possibility of constructing computational models of emotion using neural networks, this material will be of central importance.

2. Cognitive neuroscience of appraisal processes: domains of processing, temporal dynamic, and levels of processing

Since its emergence as a recognized discipline in the 1980s, the cognitive neuroscience approach was first applied to classical domains of cognitive science such as perception, action, attention, memory, and language (see Posner & DiGirolamo, 2000). A decade ago, Davidson and Sutton (1995) pointed to an emerging discipline—affective neuroscience—arguing that studies on emotion require a careful dissection of emotional processes into elementary mental operations, consistent with the approach of cognitive neuroscience (concerning the emergence of Affective Neuroscience, see also Panksepp, 1991). Distinguishing affective neuroscience from the cognitive neuroscience of emotion with epistemological and theoretical considerations is not discussed here because both approaches share the fundamental goal of analyzing emotional mechanisms in terms of their subcomponents and of understanding how these subcomponents interact in a psychologically and biologically plausible way (see Kosslyn & Koenig, 1995; Sander & Koenig, 2002). Influential models of emotion have used brain-based evidence at the systems level in order to propose a parsing of emotion into distinct subcomponents. For example, with a particular emphasis on clinical and cognitive neuropsychology, Damasio (1998) distinguished between neural systems involved in emotion and feeling. In his model, a critical function is given to somatic signals and their integration with other brain signals elicited by external events. From the behavionral neuroscience perspective, Panksepp (1998) proposed four primitive systems described as the emotional operating systems in the brain (*seeking*, *fear*, *rage*, and *panic* systems) combined with special-purpose socioemotional systems (for *sexual lust*, *maternal care*, and

Table 3
Predicted appraisal patterns for some major modal emotions

Criterion	ENJ/HAP	ELA/JOY	DISP/DISG	CON/SCO	SAD/DEJ	DESPAIR	ANX/WOR
Relevance							
Novelty							
Suddenness	Low	High/med	Open	Open	Low	High	Low
Familiarity	Open	Open	Low	Open	Low	Very low	Open
Predictability	Medium	Low	Low	Open	Open	Low	Open
Intrinsic pleasantness	High	Open	Very low	Open	Open	Open	Open
Goal/need relevance	Medium	High	Low	Low	High	High	Medium
Implication							
Cause: agent	Open	Open	Open	Other	Open	Oth/nat	Oth/nat
Cause: motive	Intent	Cha/int	Open	Intent	Cha/neg	Cha/neg	Open
Outcome probability	Very high	Very high	Very high	High	Very high	Very high	Medium
Discrepancy from expectation	Consonant	Open	Open	Open	Open	Dissonant	Open
Conduciveness	Conducive	Vcon	Open	Open	Obstruct	Obstruct	Obstruct
Urgency	Very low	Low	Medium	Low	Low	High	Medium
Coping potential							
Control	Open	Open	Open	High	Very low	Very low	Open
Power	Open	Open	Open	Low	Very low	Very low	Low
Adjustment	High	Medium	Open	High	Medium	Very low	Medium
Normative significance							
Internal standards	open	Open	Open	Very low	Open	Open	Open
External standards	Open	Open	Open	Very low	Open	Open	Open
Criterion	FEAR	IRR/COA	RAG/HOA	BOR/IND	SHAME	GUILT	PRIDE
Relevance							
Novelty							
Suddenness	High	Low	High	Very low	Low	Open	Open
Familiarity	Low	Open	Low	High	Open	Open	Open
Predictability	Low	Medium	Low	Very high	Open	Open	Open
Intrinsic pleasantness	Low	Open	Open	Open	Open	Open	Open
Implications							
Cause: agent	Oth/nat	Open	Other	Open	Self	Self	Self
Cause: motive	Open	Int/neg	Intent	Open	Int/neg	Intent	Intent
Outcome probability	High	Very high	Very high	Very high	Very high	Very high	Very high
Discrepancy from expectation	Dissonant	Open	Dissonant	Consonant	Open	Open	Open
Conduciveness	Obstruct	Obstruct	Obstruct	Open	Open	High	High
Urgency	Very high	Medium	High	Low	High	Medium	Low
Coping potential							
Control	Open	High	High	Medium	Open	Open	Open
Power	Very low	Medium	High	Medium	Open	Open	Open
Adjustment	Low	High	High	High	Medium	Medium	High
Normative significance							
Internal standards	Open	Open	Open	Open	Very low	Very low	Very high
External standards	Open	Low	Low	Open	Open	Very low	High

Abbreviations. ENJ/HAP, enjoyment/happiness; ELA/JOY, elation/joy; DISP/DISG, displeasure/disgust; CON/SCO, contempt/scorn; SAD/DEJ, sadness/dejection; IRR/COA, irritation/cold anger; RAGE/HOA, rage/hot anger; BOR/IND, boredom/indifference.

rough-housing play). With a different emphasis on psychopathology and personality factors, Gray (1994) distinguished three types of behavior (*fight*, *active avoidance*, and *behavioral inhibition*), each mediated by different neural systems and related to different emotional states. These systems are the behavioral approach system, the fight/flight/freezing system, and the behavioral inhibition system (Gray & McNaughton, 2000). Thus, any experienced emotional states may correspond to a blend of activity within all these three systems. Finally, with an emphasis on individual affective styles and psychopathologies, Davidson (1995) distinguished between processes involved in the perception and the production of emotionally significant signals, and in addition proposed differential systems in the two cerebral hemispheres underlying, respectively, approach-related emotions and withdrawal-related emotions.

Although existing models at the systems level have often considered critical emotional components—action tendencies, expression, feeling, and peripheral physiology—no model, to our knowledge, has focused on the appraisal component using a cognitive neuroscience approach. In this context, it is critical to understand how neural networks subserve the cognitive processes that drive the other emotional components. In order to achieve this goal, three fundamental aspects of the appraising brain have to be characterized: (1) the extent to which appraisals constitute the domain of processing of specialized neural networks, (2) the temporal dynamics of the neural networks sub-serving the appraisals, and (3) the extent to which dissociable neural networks are involved at different levels of processing. Each of these aspects is addressed below, with the aim of providing evidence for the usefulness of the approach (rather than of being comprehensive). In consequence, we provide a preliminary account of current perspectives regarding the development of a cognitive neuroscience model of the appraising brain (Sander & Scherer, in preparation).

2.1. Domains of processing in the appraising brain

2.1.1. Rationale of the approach

The rationale of the approach consists of constraining the functional organization of the SECs by reviewing converging evidence from the relevant cognitive neuroscience literature and by designing new experiments. In particular, brain imaging experiments of the normal human brain, and behavioral experiments testing brain-damaged patients, lead to critical constraints on the functional organization of appraisals. Moreover, connectionism may serve both as a theoretical paradigm and as an experimental field (e.g. Taylor & Fragopanagos, in press), and artificial neural network simulations of appraisal processes may lead to significant theoretical advances.

Critically, adopting a cognitive neuroscience approach to emotion may help to distinguish between alternative theories of emotional processing by providing new constraints based on the study of cerebral processes. Until now, two major classes of psychological theories of emotion have dominated research in cognitive neuroscience: *basic emotions* theories and *dimensional* theories.

First, the idea of *fundamental* or *basic* emotions can first be found in the philosophical history of psychology; for example, Descartes (1649, Art. 69) had already distinguished between six primitive emotions (admiration, love, hatred, desire, joy and sadness). Most of the recent cognitive neuroscience research on emotion has attempted to identify specific brain regions implementing distinct *basic* emotions (see Ekman, 1999) such as fear, disgust, anger, sadness, and happiness. Indeed, a large corpus of data suggests that signals of fear and disgust are processed by distinct neural substrates (see Calder, Lawrence, & Young, 2001). Functional imaging of the normal human brain (e.g. Phillips et al., 1997) and behavioral investigations of brain-damaged patients (e.g. Calder, Keane, Manes, Antoun, & Young, 2000) revealed a crucial involvement of insula and basal ganglia in processing disgust signals. On the other hand, animal research (e.g. LeDoux, 1996), behavioral studies of brain-damaged patients (e.g. Adolphs, Tranel, Damasio, & Damasio, 1994), and functional imaging in healthy people (e.g. Morris et al., 1996) suggested that the amygdala is a key structure for responding to fear-related stimuli (see also Öhman & Mineka, 2001). Mineka and Öhman (2002) even proposed that “the amygdala seems to be the central brain area dedicated to the fear module.” More tentative evidence suggests a similar segregation of processes related to anger, sadness, and happiness, particularly during recognition of facial expression (e.g. Blair, Morris, Frith, Perret, & Dolan, 1999). On the basis of neuropsychological dissociations between fear, disgust, and anger, Calder, Keane, Lawrence, and Manes (2004) and Calder et al. (2001) encouraged neuropsychologists to adopt the basic-emotions framework in order to understand and dissect the emotion system.

Second, from another perspective, all emotions are considered to be represented in a common multi-dimensional space. For example, Wundt (1905) proposed that the nature of each emotion category is defined by its position within three orthogonal dimensions: pleasantness–unpleasantness, rest–activation, and relaxation–attention. It has been argued that emotional response and stimulus evaluation might primarily be characterized by two dimensions: valence (negative–positive) and intensity (low–high) (see also Anderson & Sobel, 2003; Hamann, 2003). Critically, using functional neuroimaging, Anderson, Christoff, Stappen et al. (2003) found that amygdala activation correlated with the intensity but not the valence of odors, whereas distinct regions of orbitofrontal cortex were associated with valence independent of intensity. Similarly, Small et al. (2003) dissociated regions responding to taste intensity and taste valence: structures such as the middle insula and amygdala coded for intensity irrespective of valence, whereas other structures such as the orbitofrontal cortex showed valence-specific responses. From a theoretical point of view, Hamann (2003) commented on Anderson, Christoff, Stappen et al. (2003) results by arguing that “brain responses to odors dissociated relatively cleanly along the two major dimensions of emotion.”

Alternatively, a cognitive neuroscience account of *appraisal* processes in emotion may offer new avenues of investigation and possibly account for results that otherwise remain difficult to explain. Among the neural networks involved in emotional processing, a few critical structures have been intensely investigated, but their respective roles remain difficult to link with theories of emotion. These structures include the amygdala, ventral striatum, dorsolateral prefrontal cortex, superior temporal sulcus, somatosensory-related cortices, orbitofrontal cortex, medial prefrontal cortex, fusiform gyrus, cerebellum, and anterior cingulate (Adolphs, 2002, 2003a, 2003b; Damasio, 1998; Davidson & Irwin, 1999; Rolls, 1999). As already mentioned, it has been proposed that the insula is particularly involved in processing ‘disgust’ (Calder et al., 2001; Phillips et al., 1997). However, the insula was also found to be activated during the experience of sadness (George, Ketter, Parekh, Herscovitch, & Post, 1996), fear conditioning (e.g. Büchel, Dolan, Armony, & Friston, 1999), and processing of fearful faces (Anderson, Christoff, Panitz, De Rosa, & Gabrieli, 2003), challenging this ‘basic emotion’ approach. Moreover, Morris et al. (1998) showed that the anterior insula was responsive to increasing intensity of fear in faces, and Phelps et al. (2001, p. 437) proposed that the insular cortex might ‘be involved in conveying a cortical representation of fear to the amygdala.’ Therefore, it appears that the insula, as a structure, might not be uniquely involved in disgust-related mechanisms. Similarly, as described in detail below, the hypothesis that the amygdala is dedicated to the processing of fear-related stimuli is not supported by the cognitive neuroscience approach. In an effort to delineate the appraising brain, we feel that the rationale of the approach can be particularly well illustrated by an analysis of the computational profile of the human amygdala.

2.1.2. The human amygdala and relevance detection: towards a delineation of the appraising brain

Recently, Sander et al. (2003) discussed data from patient and neuroimaging studies in humans that suggested the notion of a critical involvement of the human amygdala in relevance detection. In this section, this issue is presented, and it is argued that a specific account of the function of the amygdala, as based on recent cognitive neuroscience research, is needed to constrain models of emotion.

Clear criteria are required to verify any hypothesis about the functional specificity of brain activity and its link to a particular appraisal mechanism. For example, using a brain imaging perspective, a key criterion is to show that differences in the activation of a brain region obtained for the proposed domain of specificity cannot be found across domains for which the particular brain response is not supposed to be specific. For instance, as mentioned above, some authors proposed that the amygdala implements a fear module, that is a device specifically dedicated to the activation of defensive behavior and associated psychophysiological responses and emotional feelings to threatening stimuli (see Öhman & Mineka, 2001). In this case, a key criterion to verify this hypothesis would be to show that the differences obtained in amygdala activation for the processing of fear-related vs. neutral stimuli are never found when comparing amygdala activation for the processing of non-fear-related vs. neutral stimuli. Another key criterion would be to show that brain-damaged patients with a selective lesion of the amygdala who show a deficit in the processing of threatening stimuli do not show a deficit in the processing of non-threatening stimuli.

Importantly, fear is not the only ‘basic’ negative emotion engaging the amygdala. Recognition of anger, sadness, and disgust can also be defective in patients with amygdala damage (e.g. Fine & Blair, 2000). Furthermore, fMRI studies show that processing faces with an expression of sadness (e.g. Blair et al., 1999), anger (e.g. Wright, Martis, Shin, Fischer, & Rauch, 2002), and even disgust (e.g. Anderson, Christoff, Panitz et al., 2003) can activate the amygdala. Therefore, the amygdala’s domain of processing is not restricted to fear-related stimuli but might extend to a much wider range of *unpleasant* stimuli. According to Paradiso et al. (1999), it might be especially implicated in processing highly arousing negative emotions, but less in the evaluation of positive events.

However, a second line of research suggests that the amygdala’s domain of computation may also include the processing of some *positive* events. In animals, the amygdala is implicated in learning and processing the reward values of external events (for review see Baxter & Murray, 2002). Interestingly, Parsons and Osherson (2001) proposed that amygdala activation observed during deductive (but not probabilistic) reasoning might be triggered by sudden insight achieved during deduction and reflects the satisfactory outcome associated with identifying the relevant solution. Critically, amygdala activation is also correlated with the processing of *positive events* such as happy faces (e.g. Breiter et al., 1996), positive words (Hamann & Mao, 2002), positive pictures (e.g. Garavan, Pendergrass, Ross, Stein, & Risinger, 2001), pleasant tastes (e.g. O’Doherty, Rolls, Francis, Bowtell, & McGlone, 2001) or expectation of pleasant tastes (e.g. O’Doherty, Deichmann, Critchley, & Dolan, 2002), erotic film excerpts (e.g. Beauregard, Lévesque, & Bourgouin, 2001), amusement-inducing films (e.g. Aalto et al., 2002), non-verbal vocalizations of laughing (e.g. Sander & Scheich, 2001), and reward (e.g. Zalla et al., 2000; see also Small, 2002). It has therefore been proposed that the amygdala codes for arousing stimuli, irrespective of valence. Hamann (2003) also suggested that the greater role of the amygdala for negative emotion might be partly confounded by the positive correlation between unpleasantness and arousal. Therefore, recent results from Anderson, Christoff, Stappen et al. (2003) and Small et al. (2003) showing amygdala activation evoked by intensity but not valence of odors and tastes also suggest a lack of intrinsic preference for negative stimuli per se when the effect of arousal is controlled (see also Gläscher & Adolphs, 2003).

Nevertheless, this proposal should be considered with caution because stimuli with apparently equal arousing values (such as fear and anger faces) do produce differential activation in the amygdala (e.g. Whalen et al., 2001). Furthermore, Adolphs, Russell, and Tranel (1999) examined a patient with bilateral amygdala damage for the arousal rating of negative and positive stimuli: the patient’s rating was impaired for negative but not positive emotions, which disagrees with the view that the amygdala might code arousal irrespective of valence. Moreover, findings of amygdala activation during the processing of low-arousal information, such as sadness-related events (e.g. Levesque et al., 2003; Posse et al., 2003), do not support the view that the amygdala might be tuned to highly arousing stimuli only. Based on the fact that the amygdala is sensitive to both signals of sadness and of fear, it was also suggested that the amygdala sub-serves a system that is activated by distress cues, that is, emotional facial expressions of fear and sadness (see Fine & Blair, 2000).

Finally, any theory of emotion should also consider that the amygdala has sometimes been found to be activated in experiments that do not manipulate the emotional value of stimuli, but rather use biologically and/or socially relevant information. In particular, the amygdala is activated when participants attribute mental states to other individuals (Baron-Cohen et al., 1999), process unfamiliar novel faces (Dubois et al., 1999; Wright et al., 2003a), view direct eye-gaze (George, Driver, & Dolan, 2001; Wicker, Perret, Baron-Cohen, & Decety, 2003), discriminate gaze direction (Kawashima et al., 1999), and process racial out-group faces (Hart et al., 2000; Phelps et al., 2000). Interestingly, a recent fMRI study (Winston, Strange, O'Doherty, & Dolan, 2002) converged with previous patient data (Adolphs, Tranel, & Damasio, 1998) by showing an involvement of the amygdala in response to faces judged as untrustworthy. Amygdala activation was also found when processing point-light sequences simulating meaningful body motion vs. non-biological movement (Bonda, Petrides, Ostry, & Evans, 1996); when hearing one's own name, as compared with a beep, during sleep (Portas et al., 2000); and when viewing highly interesting and unusual pictures even if they were emotionally neutral (Hamann et al., 2002).

Therefore, the bulk of evidence suggests that for differences assumed to reflect amygdala functions in the domain of 'fear', the domain of 'arousing negative emotions', or the domain of 'highly arousing emotions' in general, all were in fact similarly found in a variety of other distinct domains for which an amygdala involvement was initially not expected. On the basis of this evidence, it is legitimate to consider an alternative conceptual framework. On the basis of an overview of the recent literature, Sander et al. (2003) have suggested two main classes of plausible explanations for the functions of the amygdala.

First, to accommodate the multifaceted aspects of emotional processing and of amygdala functions, one kind of explanation might be that the amygdala can implement *as many processes as those that are directly suggested by the variety of experimental results*. According to this view, some subregions within the amygdala might still be considered as implementing a specific *fear module*, whereas other parts might sub-serve distinct processes. For instance, some authors (Canli, Sivers, Whitfield, Gotlib, & Gabrieli, 2002) suggested two basic amygdala processes: one engaged across all people in response to fearful expressions (reflecting the importance of detecting potential signals of danger), and another engaged more variably across people as a function of personality traits such as extraversion (determining individual responses to happy expressions). Although it is true that the amygdala is composed of different nuclei with distinct roles (Davis & Whalen, 2001; Swanson & Petrovich, 1998), the work of Barton, Aggleton, and Grenyer (2003) across species of mammals suggests that evolutionary changes in the volume of amygdala components are strongly correlated and that the amygdala may be viewed as both a structural and a functional unit. Unfortunately, it is still not possible to draw straightforward conclusions about the functional specialization of the human amygdala nuclei either from lesion or from brain imaging studies (but for attempts to do so, see Morris, Büchel, & Dolan, 2001; Whalen et al., 2001).

The second kind of explanation argues that an extensive analysis of the different types of stimuli and tasks associated with amygdala involvement may point to *a common computational profile*. Whalen (1998) linked emotion to vigilance by proposing that the amygdala may be especially involved in increasing vigilance and attention based on perceived stimulus ambiguity. According to this view, ambiguous stimuli require more information to be gathered in order for the organism to decide the appropriate behavior to engage in. Increased vigilance was defined as a potentiated neuronal responsiveness in sensory systems receiving inputs from the amygdala (Davis & Whalen, 2001; Vuilleumier, Richardson, Armony, Driver, & Dolan, 2004; Whalen, 1998). Unlike angry faces, fearful faces are ambiguous because they signal an increased probability of threat without providing clear information about its source. Given that angry faces are not as ambiguous as fearful faces, they can still activate the amygdala but to a lesser extent than fearful faces (Whalen et al., 2001). However, importantly, when angry faces are combined with ambiguous gaze direction, amygdala activation might be increased (see Adams, Gordon, Baird, Ambady, & Kleck, 2003).

In this context, an alternative account can be proposed, based on the appraisal theory of emotion, which might provide new vistas on the contribution of the human amygdala to emotion processing and may constitute the grounds for new cognitive neuroscience experiments, including neural networks simulations. From converging evidence in studies of the human brain, it can be proposed that the basic computational profile of the amygdala meets the core psychological concept of a *relevance detector* (see Sander et al., 2003). Evaluation of relevance may then elicit responses in the emotional components. These responses may include enhanced sensory analysis and enhanced encoding into memory, as well as autonomic, motor, and cognitive effects (see Fig. 1). For example, according to this view, both fearful and angry faces represent self-relevant information because they may potentially obstruct one's goal and signal the presence of danger for the organism and his or her conspecifics. However, the degree of self-relevance might depend on the appraisal of other concomitant information, such as expectations, gaze direction, familiarity, or novelty (see also Section 2.1.3).

In fact, several results in the literature are in accordance with the idea that amygdala processes do not respond just to the intrinsic valence or arousal level of an induced stimulus, but to the subjectively appraised relevance. For instance, Canli, Zhao, Brewer, Gabrieli, and Cahill (2000) showed that the degree of left amygdala activity during an encoding task was predictive of subsequent memory *only* for scenes subjectively rated as most emotionally intense. Likewise, Phan et al. (2003) found amygdala responses only when subjective ratings were incorporated in the analysis of brain activation as individual modulatory regressors. These findings indicate that amygdala activation is associated with subjective arousal and that individual variability between and within participants can influence the sensitivity for detecting amygdala responsiveness. Other brain-imaging reports indicate that perceived emotional value may vary according to participants' needs (e.g. LaBar et al., 2001; Morris & Dolan, 2001). For instance, LaBar et al. (2001) showed that the amygdala was more activated by the visual presentation of food-related stimuli when participants were hungry than when they were satiated. Morris and Dolan (2001) also observed that amygdala activation was positively correlated with recognition memory scores for food items and that participants showed enhanced recognition of food stimuli (relative to non-food) in a fasting state (relative to a satiated state). Recently, Hinton et al. (2004) found that during a hungry state, but not during satiety, there was increased activation in the amygdala when participants imagined themselves in a restaurant and chose their preferred food among items on a menu. Importantly, all items were tailored to each individual and varied in their incentive value, but no actual foods were presented to the participants.

In our view, these results represent an important step towards an appraisal approach: amygdala responses to emotional events appear strongly dependent on the subjective evaluation of these events, and on complex contextual factors. In fear conditioning paradigms, the initially neutral stimulus associated with a fear event activates the amygdala not simply because it has acquired an aversive meaning, but because it becomes, as the conditioned stimulus, highly relevant in signaling the presence of a potential threat. The result from Winston et al. (2002) showing that amygdala activity is increased in response to untrustworthy faces is also consistent with this 'relevance hypothesis'. From this perspective, Canli et al. (2002) findings (discussed above) might be re-interpreted not as revealing two different processes, but as reflecting the relevance of faces with emotional expressions. It might be that more extraverted people appraise happy faces as more relevant to their goals and needs. Social events are also particularly relevant within primate societies. As shown by a large corpus of data, social signals that are a priori non-emotionally laden, such as gaze direction, intentions, group adherence, trustworthiness, and facial familiarity can activate the amygdala (e.g. Baron-Cohen et al., 1999; Bonda et al., 1996; Dubois et al., 1999; George et al., 2001; Hart et al., 2000; Kawashima et al., 1999; Phelps et al., 2000; Portas et al., 2000; Winston et al., 2002; Wright et al., 2003b). Furthermore, even faces with neutral expressions can activate the amygdala when these faces are highly relevant to the observer (e.g. Leibenluft, Gobbini, Harrison, & Haxby, 2004; Singer, Kiebel, Winston, Dolan, & Frith, 2004). Finally, it is likely that emotion signals conveyed by intrinsic features of a particular stimulus (e.g. angry facial expression) might be modulated by the appraisal of contextual factors that determine the social meaning of a given expression: for example, a smiling face may signal sympathy if it occurs in a positive context for the viewer, but hostility if it occurs in a negative context. Indeed, contextual effects on amygdala activation were obtained by Kim, Sommerville, Johnstone, Alexander, and Whalen (2003) who showed an inverse pattern of fMRI activation in amygdala and medial prefrontal cortex depending upon whether subjects interpreted surprised facial expressions positively or negatively from simultaneous verbal information. Moreover, Maratos, Dolan, Morris, Henson, and Rugg (2001) showed that the recognition of words presented in a negative emotional context produced a simultaneous activation in both right dorsolateral prefrontal cortex and left amygdala, while words themselves were unchanged.

Recently, in wondering whether the human amygdala is specialized for processing social information, Adolphs (2003b) mentioned that it is known for a fact that the human amygdala participates in processing both the motivational properties of stimuli as well as their social properties. Then the author proposed three alternatives to explain this domain of processing of the amygdala: (1) it processes primarily motivational information and hence derivatively plays a role in processing social information, (2) it processes primarily social information but via a mechanism that can be extended to the processing of the motivational properties of non-social stimuli, or (3) it processes a category of information on which both of these depend. Our analysis and proposal that the human amygdala is critically involved in *relevance detection* corresponds to the third alternative proposed by Adolphs (2003b): the proposed role of the amygdala in appraisal processes makes it critical for a function (i.e. relevance detection) on which both the motivational and social properties of stimuli may depend.

Importantly, the amygdala is well connected to many other brain regions in order to act as a relevance detector. It receives information from the thalamus and all sensory cortices (see Aggleton, 1992), possibly together with inputs from a direct colliculo-pulvinar-amygdala pathway and indirect cortico-amygdala pathways, as suggested in animals and humans (see LeDoux, 1996; Pessoa, McKenna, Gutierrez, & Ungerleider, 2002; Phelps et al., 2001; Vuilleumier, Armony, Driver, & Dolan, 2001; Vuilleumier, Armony, Driver, & Dolan, 2003). Moreover, amygdalofugal projections to sensory cortices are massive and have been previously shown to involve all but eight of the cortical areas in the macaque (Young et al., 1994). It is also of particular interest to notice that modulatory (inhibitory) connections from prefrontal structures to the amygdala have been proposed on the basis of animal research and brain imaging studies (Irwin et al., 2004). A neural network connecting the left and right amygdala through fontal lobes was suggested by the analysis of seizure propagation in epilepsy using depth electrodes (Lieb, Dasheiff, & Engel, 1991; Wilson & Engel, 1993). In keeping with such amygdala-frontal connectivity, an fMRI study by Hariri, Bookheimer, and Mazziotta (2000) showed that responses to negative emotional expressions decrease in the amygdala when there is a simultaneous increase in right prefrontal activity, presumably mediating some top-down regulation of amygdala activity (see also Hariri, Mattay, Tessitore, Fera, & Weinberger, 2003, for consistent results). Similarly, a neural network for emotional regulation involving interactions between lateral and medial prefrontal cortices, amygdala, and orbito-frontal cortex was implicated in a recent fMRI study (Ochsner, Bunge, Gross, & Gabrieli, 2002). Overall, this large variety of cortical and sub-cortical projections might provide the amygdala with rich information about many properties of sensory events (including motivational and social properties) and their context of occurrence, as well as the ongoing goals and needs of the organism.

2.1.3. Novelty detection: an attempt to bridge appraisal processes and cognitive neuroscience

To illustrate our theoretical approach aimed at bridging a psychological model of emotion and the cognitive neuroscience approach, we propose to discuss deeper the novelty check. This predicted first check in the sequence of appraisal process (Scherer, 1984) has been broadly studied in cognitive neuroscience and the accumulated knowledge could help in understanding this process in the context of emotion generation and suggests elements for future implementation in artificial neural networks.

A huge corpus of studies is aimed at identifying the anatomical structures and associated functional networks subserving novelty detection. In order to achieve this aim, researchers used various cognitive tasks, experimental designs, and brain imaging techniques (e.g. electroencephalography [EEG], or fMRI) as well as patient studies.

Several studies showed an increase of attentional resources elicited by the presence of new stimuli using visual exploration measurement (Daffner, Scinto, Weintraub, & Guinessey, 1992; Daffner, Scinto, Weintraub, Guinessey, & Mesulam, 1994). Several evoked potential components were shown to be generated or affected by the experimental manipulation of the novelty. The most studied components, for the appraisal of novelty, are the negativity of discordance or 'mismatch negativity' (MMN), the N200 or N2, and the P300 or P3. It is important to note that the majority of the paradigms investigating the appraisal of novelty used the auditory modality, in the form of the oddball paradigm. In such a paradigm, participants are required to discriminate rare information in a flow of background information; a sequence of stimuli frequently presented is interrupted by the presentation of a rare stimulus. The oddball paradigm can also be used with patterns of more complex stimulation, a repetitive one interrupted by another pattern. The first component related to the appraisal of novelty is the MMN (appearing about 150 ms post-stimulus), followed by the N2b component (appearing about 200 ms post-stimulus) and then by the P300 component (appearing about 300 ms post-stimulus), which can be dissociated into the P3a and the P3b components. The MMN is distinguished from N2b by a more frontal distribution, whereas the N2b component prevails on posterior sites. In addition, the MMN presents an inversion of polarity at the level of the mastoids. These two components can fuse in only one N2 complex located on median derivations. The MMN is specific to the auditory modality and may be generated by two distinct processes: (i) within the primary and associative auditory cortices and (ii) with a frontal source (Friedman, Cycowicz, & Gaeta, 2001). This frontal source could be the signature of a call for the orientation of attention by a network linking the auditory cortex to the frontal areas, making it possible to allocate resources on this atypical stimulation dissociated from the background stimuli. Note that this component is task-independent, independent of voluntary attention, and appears even if the participant is engaged in another task; it would thus be a sign of an automatic, pre-attentional orientation towards the deviating stimulus in auditory modality. The amplitude of this component is proportional to a measurement of the stimulus deviance; moreover, when the deviance becomes significant, the MMN is followed by a positive wave or P3a. This P3a component would be a sign of an involuntary orientation of attention. Lyytinen, Blomberg, and Naeaetaenen (1992) measured peripheral physiological parameters and event-related potentials (ERPs). They observed a correlation of these peripheral activations with the amplitude of the P3a component (but not with the MMN component). P3b would occur a few tens of milliseconds after P3a or could even overlap with it, forming a P300 complex. The P300 wave is sometimes called the 'late positive component' (Sutton, Braren, Zubin, & John, 1965). In the oddball paradigm, the amplitude of the P300 wave is a function of the scarcity; the rarer the stimulus, the more significant the amplitude of this wave. This wave would thus be made up of two subcomponents: P3a culminating towards 250 ms and P3b culminating towards 350 ms. The distribution of P3a is anterior (fronto-central location), whereas P3b is posterior (centro-parietal) (Gil, 1997).

Recently, Simons, Graham, Miles, and Chen (2001) unsuccessfully attempted to separate P3a and P3 novelty in two different frontal components. Earlier work studied the two above-mentioned waves: they described a component N2–P3 of novelty, a terminology that is used by many authors (e.g. Naeaetaenen, & Gaillard, 1983; Rohrbaugh, 1984), as being different from the component N2–P3 related to a target stimulus, which presents a posterior distribution on the scalp and a longer latency (Picton, Champagne, & Kellet, 1992; Ranganath, & Rainer, 2003; Squires, Squires, & Hillyard, 1975). Daffner et al. (1998) were able to reveal a link between the genesis of a broad component of novelty N2–P3 and the duration of visual exploration of stimuli by the participants. The novelty detection would function to orient the attention, allowing a thorough treatment of the new stimulus. If the stimulus was to be presented several times, it would then be represented in memory and therefore no longer processed as being new. Early electrophysiological studies of novelty detection had already shown that the repeated presentation of a stimulus causes a fast reduction in the P3 wave of novelty (Courchesne, Hillyard, & Galambos, 1975). This reduction in the P3a component, by repeated exposure of the stimulus, was reproduced in many other studies (e.g. Friedman & Simpson, 1994). Baudena, Halgren, Heit, and Clarke (1995) used depth intracranial electrodes and obtained results supporting the notion that the component N2–P3 would reflect the activity of neural networks implemented in the dorsolateral prefrontal and in the orbito-frontal cortex, as well as in the cingular cortex and the gyrus rectus. According to the authors, this component would reflect the working memory-based comparison process between a stimulus and the immediately preceding stimuli. Moreover, Daffner et al. (2000) showed that the familiarity of information can also modulate the component of novelty N2–P3. Therefore, this component does not only reflect the comparison between a stimulus and those presented immediately before, but also the comparison with encoded stimuli in long-term memory. Knight (1984) obtained empirical evidence compatible with a prefrontal implementation of the neural network subserving novelty detection. Consistently, Mecklinger and Ullsperger (1995) used a dipole analysis to show a frontal localization of the neural generators of the P3a wave, which was not the case for the component related to the target stimuli (see also Ranganath, & Rainer, 2003). Using a traditional oddball experiment, Delplanque, Silvert, Hot, and Sequeira (2005) showed a valence effect on the P3b component, but not on the P3a component. These results were interpreted by the authors as suggesting that the memory updating process may be modulated by the affective valence of unpredictable disturbing stimuli, even if the task does not require any explicit emotional categorization. Such results may be interpreted in the framework of the componential approach to emotion, not as revealing an interaction between ‘emotion and cognition’, but rather as revealing electrophysiological evidence for the temporal unfolding of the appraisal component of emotion.

Brain imaging studies measuring the hemodynamic response (e.g. PET and fMRI) also contributed to a better understanding of the cerebral structures involved in the appraisal of novelty. FMRI studies often compared brain structures involved in novelty detection vs. stimulus-target detection, similar to the oddball paradigm used in EEG studies. In the visual modality, McCarthy, Luby, Gore, and Goldman-Rakic (1997) confirmed an activation of the bilateral medial frontal gyrus areas, the bilateral inferior parietal lobe (supramarginal gyrus), and the posterior part of the cingular cortex. Consistently, Friedman et al. (2001) reviewed eight fMRI studies suggesting an involvement of the dorsolateral frontal areas and the temporo-parietal junction for the novelty appraisal, but only of the temporo-parietal junction for the detection of target stimuli. Moreover, sensory cortices specific to the sensory modality investigated were revealed (e.g. the superior temporal gyrus for the auditory modality and the occipital areas for the visual modality). To summarize, the contribution of functional neuroimaging in the study of *processes* and *cerebral structures* subserving the novelty check was impressive during the last 10 years. Converging evidence suggests that the appraisal of novelty involves a distributed cortical network including four main structures: the dorsolateral prefrontal cortex, the temporo-parietal junction, and, although evidence is more tentative, the posterior hippocampus and the cingular cortex. Recently, Yamaguchi, Hauls, D’ Esposito, and Knight (2004) explained that mechanisms involved in novelty detection consisted not only in processes related to the P300, but also in a network involving prefrontal and hippocampal areas whose activity would increase for novel stimuli and signal a phase of attentional orientation (for the prefrontal cortex) and a phase associated with habituation (for the hippocampus). In addition, these areas showed a rapid activity reduction (quadratic) with repeated presentations of the stimuli, independent of the voluntary attentional focus. Two fMRI studies (Schott et al., 2004) further showed that the hippocampus processes are accompanied by an activity of the tegmental ventral area and of the medial nigra substantia during the novelty appraisal independently of the task (identification vs. spatial localization). The processes of memory storage and retrieval involving a septo-hippocampal loop were studied through artificial neural networks constrained by animal data in vivo (Meeter, Murre, & Talamini, 2004). This work proposed a novelty detection model based on the modulation of the acetylcholine level of the hippocampus underlying memory storage and future retrieval.

Wright et al. (2003a) used fMRI to show that novel neutral faces can activate the amygdala, the substantia innominata, and the inferior temporal cortex. Consistent with predictions driven by the appraisal theory, such a response was shown to be sensitive to personality differences (e.g. inhibited temperament). In particular, it was found that adults who had been categorized in the second year of life as inhibited, compared with those previously categorized as uninhibited, showed greater response to novel vs. familiar faces within the amygdala (Schwartz, Wright, Shin, Kagan, & Rauch, 2003).

The distinction between conscious and voluntary evaluation processes on one hand, and implicit and involuntary processes on the other, is central in the study of novelty detection. Various works showed the importance of distinguishing the neural networks underlying processes that are different according to the task that the participant is required to perform. Berns, Cohen, and Mintun (1997) manipulated the stimuli occurrence sequence by repeating certain sequences but not others, the latter being thus considered unconsciously as new. Their results indicated an activation of the ventral striatum and the anterior cingular cortex, as well as the left premotor areas. The study of Opitz et al. (1999) revealed a neural network consisting of the left and the right transverse temporal gyri, as well as the superior temporal gyrus. The involvement of a right anterior frontal area for the MMN cannot be excluded; it was also suggested by the work of Scherg, Vajsar, and Picton (1990). The study of a very fast habituation response, a quadratic reduction in the activity measured by fMRI within the bilateral frontal areas and in the hippocampus, also confirmed the existence of a fronto-hippocampus neural network, largely independent of the voluntary attention, that detected the novelty and that could allow the storage in the long-term memory of the considered event (Yamaguchi et al., 2004). The unconscious change detection would involve a network consisting of the right dorsolateral cortex used for the maintenance in memory of the contextual information and the ventral striatum whose activity would be associated with the implicit detection of a violation of an implicitly learned sequence (Berns et al., 1997).

Results from clinical neuropsychology are also relevant to the study of novelty detection. Evoked potential recordings in patients with cerebral lesions of the frontal lobes made it possible to confirm the importance of the aforementioned structures in novelty detection (Daffner et al., 2000). Several studies confirmed that the dorsolateral prefrontal cortex would be essential for the novelty appraisal. Indeed, patients with lesions of this part of the frontal cortex show a significant reduction of the novelty P3 wave, as well as of the duration of visualization of a new stimulus. Moreover, they do not show a significant reduction in the P3 wave related to the detection of the target stimuli. Supplementary evidence consists of the strong correlation found between the duration of visual exploration and the novelty P3 wave. A path analysis confirmed the importance of the novelty P300 to explain the variance observed in the duration of visual exploration of the new stimuli. Other studies testing brain-damaged patients highlighted the importance of the prefrontal dorsolateral cortex in the detection of novelty. Knight (1984) tested a group of patients with unilateral lesions of the prefrontal dorsolateral cortex and observed a significant reduction of the amplitude of the P3a component, whereas this was not the case for the P3b posterior component related to the detection of the target stimulus. In this study, Knight (1984) also demonstrated a significant reduction of the P3a wave concomitant with the stimulus repetition in control participants, but not in patients with lesions of the prefrontal dorsolateral areas. The involvement of the temporo-parietal junction in the genesis of the P3a in auditory modality was shown by other patient studies. Indeed, patients with lesions in these areas presented a reduction and even a suppression of the two P3a and P3b components during an oddball paradigm in auditory modality. Similar results were found in the somesthesic modality (Ranganath, & Rainer, 2003). It should be noted that parietal lesions do not induce any reduction of these two components (Knight, Scabini, Woods, & Calyworth, 1989). The patients with posterior hippocampal lesions also showed a significant reduction of the P3 components, indicating the importance of this structure in the distributed neural network subserving novelty detection (Knight, 1996). Studies with Parkinson patients showed a deterioration of the P3 wave in relation to difficulties in novelty detection. These novelty detection deficit and wave deterioration were linked with deficits for neuropsychological tests such as the Wisconsin Card Sorting Test (WCST) and verbal fluency tests known for their sensitivities to frontal lobe dysfunctions. Moreover, a reduction in the amplitude of the P3 wave on the anterior sites of the scalp was shown among these patients. The participants having the worst scores to the WCST also showed a more significant reduction of the wave amplitude on the anterior sites (Tsuchiya, Yamaguchi, & Kobayashi, 2000).

These various studies all converge towards the evidence for a large distributed neural network subserving novelty detection. This network would primarily consist of, on one hand, the frontal dorsolateral cortex, and on the other hand, the temporo-parietal junction and the posterior part of the hippocampus (Friedman et al., 2001), as well as the amygdala. At the functional level, the novelty appraisal would induce attention orientation towards the new stimulus, thus allowing resource allocation and awareness of the new stimulus, as well as further subsequent appraisal processing and changes in the other emotional components (see Section 1 and Fig. 1).

As illustrated above, in order to address the questions relative to the timing of psychological processes, brain imaging techniques such as EEG and magnetoencephalography (MEG) are the best non-invasive approaches, even if the timing question is progressively taken into account in fMRI analyses. The rapidity of brain processes related not only to sensory inputs but also to psychological processes can take a few tens of milliseconds to be computed by distributed neural networks. The temporal resolution of EEG and MEG can be at the sub-millisecond time scale and allows accurate processing of the timing of stimuli and related endogenous processes to be addressed.

2.2. Temporal dynamics of the appraisal sequence

In spite of a growing consensus among the appraisal theorists on which dimensions constituting the appraisal process are necessary to explain and predict human emotional reactions, the question of the temporal dynamic remains unsolved (Scherer, 2001). Several theoretical points of view are opposed and suggest different visions of the importance of the time process within appraisals in the genesis of emotion. Beyond the intrinsic interest of the understanding of the human processes involved in the genesis of emotion, the temporal dynamic issue is critical for designing artificial neural networks. Realistic modeling of the neural functioning of organisms using artificial neural networks should take into account the issues concerning the temporal dynamic of emotional processes.

2.2.1. *Theoretical debate on the sequential nature of appraisal processes*

The sequence of the various appraisals is, according to authors, fixed or flexible. Scherer (1984), in his model, predicted that the sequence of the appraisal processes is fixed, contrary to Smith and Lazarus (1990) who postulated flexibility in the order of their appearance. This order is influenced by the characteristics of the event, the previous situation, or cognitive evaluations. In their theoretical suggestions, Smith and Lazarus (1990) proposed that it is not necessary that a given organism process information sequentially, and that the elicitation of activity and the order in which appraisal processes appear depends upon the contingencies of the environment. For these authors, flexibility is particularly true when the processes are unconscious and are processed at a schematic and/or automatic level. Their argument is based on the theory of associative networks developed primarily by Bower (1981), but also Isen (1984, 1987), and used to explain the effects of the emotions in social context (Niedenthal, & Showers, 1991). Smith and Lazarus estimate that this type of process allows a very fast unconscious computation of information and that it is not necessary to postrate a specific sequence to give an account of these processes. Smith and Lazarus (1990, p. 629) write: “One way in which the operation of schematic processing can be understood is by using the concepts of activation and associative networks commonly invoked in the study of memory (…) In considering this type of mechanism, it is not necessary to think of the appraisal process as following a fixed or predefined sequence, since the full appraisal meaning associated with the past experience(s) can be activated in a single step”. To our view, associative networks cannot be considered as being at the same *level of explanation* as appraisal processes. In fact, we have difficulties in understanding how an appeal to associative networks may allow theoretical advances in the understanding of emotional processes. The fact that unconscious processes are involved in emotional processes is unquestionable, but to our view this does not at all imply that association rules explain unconscious processing. Rather, a growing number of studies indicate that the automatic and unconscious processes are also complex and that they can be carried out according to a sequence suggested by dynamic and temporal models (Lewis, in press). For example, in the domain of emotional facial expression, Adolphs (2002) suggested a sequential process, implying the involvement of various cerebral structures in the perception of emotional facial expressions.

Smith and Lazarus (1990, p. 630) suggested, however, that the concept of sequence can be proposed for appraisal on a conceptual level: “Automatic or schematic processing, as we have described it, is quite passive, and it is important not to lose sight of the fact that humans are sentient, problem-solving beings who actively seek to understand the world and their reactions to it (…) Although conceptual processing of appraisal components could perhaps follow predefined sequences, as Scherer (1984) has suggested, we are wary of a stage theory, since whatever issues and aspects of the encounter seem especially salient may well pre-empt attention at any given moment.”

It seems, in this proposal, that the authors amalgamate the concept of microgenesis of temporal sequence of the process of appraisal as proposed by Scherer with the concept of information processing on a conceptual level, implying a progressive sequence of the informational elements for reasons of logic, forcing a certain sequence. We point out that the concept of temporal sequence was suggested not only at the conceptual level but also precisely at the schematic and sensorimotor levels (Leventhal & Scherer, 1987; see Section 1.3 above). Ellsworth (1991a, 1991b) reminds us that the sequence of information processing elicited by events or stimuli during an emotional episode was for a long time raised by the issues opposing James-Lange’s peripheralist theories to Cannon’s position (e.g. James, 1884; Cannon, 1927). Within the framework of appraisal theories, Ellsworth (1991a, 1991b, p. 153) wrote: “Appraisal theories put forward a different set of questions about an emotional episode. They suggest that full-blown emotions are not unitary, that not all of the components of the subjective experience, or of the peripheral response, emerge simultaneously. Some appraisals may be more immediate than others, suggesting that any given emotional experience may be broken down into a microsequence of events both centrally and peripherally.”

Ellsworth supports the concept of micro-sequence in appraisal process, at least for early checks like novelty. Moreover, in agreement with Scherer’s proposal (e.g. Scherer, 1981, 1984a, 1984b), Ellsworth proposed that novelty appraisal allows the orientation of attention and thus the investment of mental resources, allowing a thorough treatment of the stimulus or event. This concept of novelty can therefore be linked to the concept of orientation of attention elicited by a very fast evaluation that could be carried out, at least partly, at an automatic level (Siddle & Lipp, 1997; Sokolov, Nezlina, Polyanskii, & Evtikhin, 2002). In contrast to Scherer’s proposal, Ellsworth (1991a, 1991b, p. 154) suggested that “the sequence of appraisals, once attention has been aroused, may be somewhat variable.” The rationale is that appraisal of uncertainty, appraisal of agency, or even conduciveness could take place at different temporal periods, according to the event contingencies. Ellsworth thus proposed that the appraisal of novelty would indeed precede all other appraisals but that the consecutive sequence of checks would be strongly influenced by the characteristics of the event or stimulus.

The fact that Scherer (1981, 1984a, 1984b, 2001) proposed a fixed sequence of occurrence of the checks does not exclude parallel processing at all. Furthermore, although the occurrence of a certain evaluation is predicted at a given time, the model proposes that this can possibly continue at other levels of processing (Leventhal & Scherer, 1987). Scherer (1984) suggested that the appraisal process consists of a very rapidly occurring sequence of hierarchically organized stimulus processing steps. This sequence assumption does not deny the existence of parallel processing.

As discussed above (see Section 2.1.3), many EEG studies addressed novelty processing and highlighted the rapidity and the unconsciousness of novelty detection. This corpus of studies demonstrates that the processes related to novelty detection are antecedent to those related to relevance detection (Ranganath & Rainer, 2003). The well-known P3a related to novelty processing occurs ~70 ms before the P3b related to target stimulus. Therefore, the initial novelty processing seems indeed to precede the relevance detection in this type of oddball paradigm. However, we would like to underline the possibility of even earlier unconscious processes related to novelty—these processes may be initiated in the hippocampus as suggested by animal studies (Kesner, Lee, & Gilbert, 2004; Meeter et al. 2004).

2.2.2. Behavioral empirical evidence

Scherer (1999b) investigated the sequential nature of appraisal processes in an experimental paradigm in which the *sequence* of information associated with the various checks was systematically manipulated. In three successive experiments, the importance of the sequence of the presentation of information was highlighted, on the one hand through speed recognition and on the other hand through the accuracy of the decision made according to the emotion felt by the protagonists involved in the narration. These results represent indirect evidence for the sequence hypothesis during appraisal processes. Another recent psychophysiological experiment supported the sequence hypothesis: variations in facial expression indicators (*corrugator* and *zygomaticus*) suggested earlier effects of *relevance detection* than effects of appraisal of *goal conduciveness* (Aue, Flykt, & Scherer, submitted for publication). The study of Wehrle et al. (2000), investigating the temporal aspects of the decoding of emotional facial expressions and its progressive 'building' through successive checks, also supports the temporal sequence hypothesis.

2.2.3. Electrophysiological evidence on appraisal sequence

In order to address systematically the question of the dynamic unfolding of appraisal processes, we designed a series of electroencephalographic studies manipulating novelty, goal relevance, intrinsic pleasantness, and goal conduciveness. The first study addressed the sequence hypothesis for the *novelty*, *intrinsic pleasantness,* and *goal relevance* checks. The second one compared the intrinsic pleasantness check with the goal conduciveness check (Grandjean & Scherer, in preparation).

Results of the first study are reported in detail elsewhere (Grandjean & Scherer, 2003; in preperation); for the current article we would like to highlight the main results but, even more important, the method used to systematically address the timing issue.

Information processing at the cerebral level can be studied by investigating the modifications of the topographical configuration of the electrical fields through time measured at the scalp by EEG. Michel et al. (2004), and Pascual-Marqui, Michel, and Lehmann (1995) defined a procedure of analysis that takes into account all electrodes rather than focusing analyses on one or two electrodes as is the case in traditional trace analyses. The succession of topographic configuration of electric fields (one configuration at each time measured) could be summarized by a series of stable topographic maps. The resulting maps can be fitted to different experimental conditions and used to infer the neural network involved at a certain step of information processing by resolving the so-called inverse problem (Michel et al., 2004). A cluster analysis by K-means allows the determination of the different maps during information processing (Michel, Seeck, & Landis, 1999). These maps are supposed to correspond to functional microstates of the brain or 'mind-states' during this information processing (Lehman, 1987). The number of maps is defined by a cross-validation index that determines the number of topographic maps needed to explain a maximum of variance of data with a minimum of overlapping (Michel et al., 2004).

As mentioned above, this method was used in a study during which novelty, relevance, and intrinsic pleasantness checks were systematically manipulated in the visual modality (pictures from the International Affective Picture System; Lang, Bradley, & Cuthbert, 1999). Novelty was manipulated by the occurrence of new visual stimuli during a train of already seen stimuli (new vs. already seen stimuli). Relevance was defined by the task: participants were required to detect whether the presented stimulus corresponded to a specific target or not (relevant stimuli vs. non-relevant). Finally, intrinsic pleasantness was defined by the ratings in the valence dimension of the stimuli as determined by Lang et al. (1999); neutral, positive, and negative stimuli were used. Briefly, the results highlighted an early specific topographic map for the novelty check and another one specific to the relevance process; the novelty map occurred about 80 ms after the onset of stimuli while the relevance map occurred about 150 ms after the onset of stimuli (Grandjean & Scherer, 2003; in preparation). No specific map was found for the intrinsic pleasantness conditions, but analyses indicated an increase of the global field power (GFP) intensity around 100 ms after the onset of stimuli for the intrinsic pleasantness check—the negative stimuli inducing a higher GFP compared with the positive and the neutral stimuli (Grandjean & Scherer, 2003; in preparation). Several other electrophysiological components, probably elicited by specific processes related to novelty, relevance, and intrinsic pleasantness, occurred at about 300 ms and later. These late electrophysiological modulations could reflect continuous information processing occurring in parallel ways at different levels of processing.

This summary of results from a study using the electrophysiological approach highlights the usefulness of investigating the temporal unfolding of appraisal processes during emotion generation. On the one hand, the sequence hypothesis of early checks was not rejected, and, on the other hand, results suggest that appraisal seems to be subserved by different processes, at different levels of processing, and that these processes may be related to different 'mind-states' as a function of the manipulated checks. This continuous appraisal of the various manipulated dimensions, and the fact that checks are not discretely and 'once and for all' computed, shows the potential importance of implementing a sequential aspect in artificial neural networks. Even if sequential, early, specific stages of processing—with efferent effects on different subsystems of an organism—is an indicator of the sequential nature of appraisal processes, this does not exclude the possibility of continuous appraisal. This continuous computation, for a given check, could reflect a process at different levels of processing, informing other neural networks involved in awareness and action preparation.

Another way to investigate and model a process like *novelty detection* is (i) the wavelet approach or time frequency analyses and (ii) the use of an oscillatory model in an artificial neural network (Borisyuk & Kazanovich, 2004). The examination of oscillatory signals in EEG using wavelet techniques or other time frequency analyses allows the study of mechanisms involved in different stages of information processing. Novelty detection and encoding processes have been studied in animal and humans linked with theta frequency elicited by activity in neural networks of the hippocampus for information encoding and retrieval (Lisman & Otmakhova, 2001). Recently, Borisyuk and Kazanovich (2004) designed an oscillatory model based on electrophysiological data in which the tonic theta phase during the appearance of a new stimulus was gradually changed to a phasic reaction during the repeated presentation of the same stimulus. Experimental studies investigating the high frequency in the gamma range and the temporal synchronization of spatially distributed neural networks involved in representational processes may also be a new way to understand the integrated representation of the *feeling component* (Scherer, 2004).

In conclusion, it seems to us that in order to design a realistic artificial neural network that is aimed at modeling the complexity of emotional processes—including emotion generation—it will be necessary to take into consideration both the dynamic temporal unfolding of appraisal processes as well as (as discussed below) the levels of processing.

2.3. Levels of processing in the appraising brain

2.3.1. Rationale of the approach

In order to set apart the neural networks involved in the various levels of processing, the rationale of the cognitive neuroscience approach is similar to that used for the *domains of processing* (see Section 2.1), but with a particular emphasis on two research strategies. First, one can consider that some events might elicit emotions because of their basic sensory properties (e.g. patterns of movements for snakes or spiders, spatial frequencies for faces, or harmonics for musical stimuli). In this context, a bottom-up approach may be used in order to investigate the basic features of emotional elicitors that drive an elementary course of processing the relevant primitives in the perceptual signal. Second, one can consider that some events might be differentially processed at separate levels as a function of current goal-need demands or task requirements (e.g. explicit/implicit processing, conscious/unconscious processing, degree of intentionality, type of attention). In this context, a top-down approach may be used in order to investigate how the neural processing of the very same stimulus is affected by a modulation of the task setting.

Appraisal theories of emotion have proposed that the appraisal process might take place at three different levels (see Section 1.3) but to our knowledge, the specific levels of processing suggested by appraisal theories have never been the focus of cognitive neuroscience research. Despite the lack of specificity in the approach, brain-based evidence from the two research strategies aforementioned suggests that multiple levels of processing are likely to be involved in the appraisal of emotional events. Examples of these strategies are given below, with the aim of providing evidence for the usefulness of the approach.

First, resulting from the 'bottom-up strategy', some cognitive neuroscience data suggest that basic sensory properties may elicit responses in neural networks that are critical for emotional processing. For example, Vuilleumier et al. (2003) took advantage of the fact that high and low spatial frequency information in visual images are supposed to be processed by distinct neural channels in order to investigate whether dissociated neural networks show distinct spatial frequency sensitivities for processing faces and emotional expressions. The authors used fMRI to show that neural responses in the fusiform cortex, and effects of repeating the same face identity upon fusiform activity were greater with intact or high-spatial-frequency face stimuli than with low-frequency faces, regardless of emotional expression. In contrast, the authors showed that amygdala responses to fearful expressions were greater for intact or low-frequency faces than for high-frequency faces. Interestingly, an activation of pulvinar and superior colliculus by fearful expressions occurred specifically with low-frequency faces, suggesting that sub-cortical structures may provide coarse fear-related inputs to the amygdala. These results are highly compatible with the proposal of the existence of the sub-cortical pathway sub-serving some appraisal processes (see below, Section 2.3.2). Recently, Whalen et al. (2004) took advantage of the fact that the eye region of the face is a key region where expression information is extracted (e.g. Adolphs et al., 2005) in order to investigate whether the amygdala is sensitive to fearful eyes presented in isolation. The authors used fMRI to show that the larger size of fearful eye whites, as compared with happy eyes, is sufficient to modulate amygdala responsivity in a backward masking paradigm that decreased participants' awareness of the presence of the eyes. Such a result is of particular interest because it shows that primitive elements of a complex social signal (e.g. the white of the eye—sclera—in a fearful face) can be appraised by a neural network including the amygdala.

Second, resulting from the 'top-down strategy', cognitive neuroscience data suggest that some neural systems are engaged in a rather involuntary and implicit manner, relatively independent of attention, whereas other systems may require attention and more extensive and effortful evaluation within the cognitive system (see Compton, 2003; Robinson, 1998; Scherer, 1993). For example, Lane, Fink, Chau, and Dolan (1997) showed that a region of the anterior cingulate extending to the medial prefrontal cortex was more activated when participants were required to process the emotional valence (positive, negative, or neutral) than when they were required to process the setting (indoors, outdoors, or neither) of emotional pictures. Using the same task, Gusnard, Akbudak, Shulman, and Raichle (2001) confirmed these results and highlighted the importance of the medial prefrontal cortex in explicit emotional evaluation. These findings might reflect the functions of the anterior cingulate and the medial prefrontal cortex in emotional experience (Damasio, 2000; George et al., 1996; Ketter et al., 1996; Lane et al., 1998; Reiman et al., 1997). Together with the inferior frontal gyrus and the amygdala, the anterior cingulate and the medial prefrontal cortex might form a network that may be part of the neural circuitry sub-serving emotion regulation (see Davidson, Putnam, & Larson, 2000). Interestingly, using hybrid stimuli containing faces with different expressions at different spatial frequencies in the image, Winston, Vuilleumier, and Dolan (2003) demonstrated that emotional information within low-spatial frequencies elicited orbitofrontal cortex responses only when this particular frequency band was reported by the participants, suggesting that frontal responses may specifically reflect the conscious emotional percept, whereas increased responses to fearful expressions in the fusiform cortex were independent of a conscious percept.

Following our discussion concerning the *domain of processing* of the amygdala and its proposed role in relevance detection, it seems critical to investigate the level(s) of processing at which the amygdala is involved. Brain imaging studies revealed that the amygdala is sensitive to non-recognized fearful faces that are task irrelevant and presented out of the focus of consciousness (Morris et al., 2001; Morris, Öhman, & Dolan, 1998, 1999; Whalen et al., 1998) and spatial attention (Vuilleumier et al., 2001). Amygdala involvement in the evaluation of non-consciously perceived emotional stimuli is also suggested by the study of blindsight patients (e.g. de Gelder, Vroomen, Pourtois, & Weiskrantz, 1999; Pegna, Khateb, Lazeyras, & Seghier, 2004) and neglect patients (Vuilleumier et al., 2002; Vuilleumier & Schwartz, 2001b). Moreover, it was shown that the processing of negative words (Isenberg et al., 1999) and faces (e.g. Gorno-Tempini et al., 2001) that are in the focus of attention, but incidentally processed, activates the amygdala. We mentioned above that the amygdala is well connected to many other brain regions in order to act as a relevance detector. Importantly, there is evidence that the amygdala may be a central constituent of a sub-cortical pathway that was proposed to be involved in the non-conscious and automatic processing of some emotional stimuli. The functional anatomy of this sub-cortical pathway is briefly described below.

2.3.2. The sub-cortical pathway

Anatomical and functional evidence suggests the existence of dual-route architecture in the appraising brain, consisting of a direct sub-cortical pathway and an indirect cortical pathway to the amygdala. Fear conditioning experiments in rats have shown the existence of a direct sub-cortical pathway from the auditory thalamus to the amygdala (see LeDoux, 1996). Critical results were obtained by Morris et al. (1999) (see also Morris et al., 2001), who showed that regions of the pulvinar and superior colliculus covaried positively with amygdala activation during masked visual presentations of conditioned faces. These results led authors to the conclusion that the emotional value of visual stimuli could be detected by a colliculo-pulvinar-amygdala pathway. Results showing that recognition of emotional stimuli is possible in a blindsight patient also suggest that this pathway exists in humans (e.g. de Gelder et al., 1999; Pegna et al., 2004). In consequence, some appraisals may apply at a certain level of processing that bypasses the visual cortex.

Such a sub-cortical pathway to the amygdala suggests that relevant events that do not require deep processing to be detected may be appraised from salient perceptual signals (such as low spatial frequency information in fear faces). Another critical issue in considering the levels of processing in the appraising brain consists of investigating whether the involvement of the amygdala—and other brain structures—in appraisals is a function of attention.

2.3.3. Appraisal processes and attention in the brain

Given the flow of events entering the cognitive system, together with its processing capacity limitations, a critical function shared by both *emotional* and *attentional* processes should be to prioritize the processing of pertinent events, relative to neutral events, leading to enhanced perceptual analysis, memory, and motor action (see Compton, 2003; Lewis, in press; Scherer, 2001, 2004; Wells & Matthews, 1994). As described above, appraisal theories of emotion have proposed that an early and critical evaluation process is responsible for detecting the extent to which stimulus events are relevant for the momentary hierarchy of goals and needs of the individual, possibly leading to an enhancement of processing resources and a modulation of attentional processes towards these events (see Fig. 1). One of the first experimental results supporting this proposal was the ‘own name effect’ obtained in a dichotic listening paradigm. Moray (1959) showed that when a participant is presented with his/her own name in the to-be-ignored ear while performing a primary task on stimuli heard in the other ear, this task-irrelevant but self-relevant information was more likely to be involuntarily processed and influence performance relative to other types of information (see also Compton, 2003; Robinson, 1998). Similarly, a number of recent results suggest that visual-relevant events can also capture attention more readily than neutral events (e.g. Mack & Rock, 1998; Pourtois, Grandjean, Sander, & Vuilleumier, 2004; Vuilleumier, 2002; Vuilleumier & Schwartz, 2001a, 2001b). For example, Pourtois et al. (2004) investigated the temporal dynamic of spatial biases in attention towards fearful faces, using evoked potential recordings in healthy volunteers. Results suggested that activity in the visual cortex might be enhanced by fear cues as early as 90 ms post-stimulus onset, and that such an effect can facilitate sensory processing of a subsequent stimulus appearing at the same location by rapid focusing of spatial attention.

To date, most brain imaging studies on interaction effects of emotion and attention have concerned the visual domain (see Taylor & Fragopanagos, in press), but little is known about the neural substrates involved in processing emotional signals from auditory stimuli and, in particular, from the affective prosody in human voices. In line with behavioral results, recent brain imaging data show that the emotional value of visual stimuli can strongly influence neuronal responsiveness in sensory and memory systems (e.g. Armony & Dolan, 2002; Hadjikhani & de Gelder, 2003; Pourtois et al, 2004; see Adolphs, 2004). Thus, faces with a fearful expression may not only activate the amygdala, but may also produce greater activation of face-selective areas in the fusiform cortex (Armony & Dolan, 2002; Vuilleumier et al., 2001, 2004), presumably through direct feedback from the amygdala (Davis & Whalen, 2001; LeDoux, 1996; Vuilleumier et al., 2004). In the visual domain (e.g. for faces), it has been suggested that such emotional modulation of perceptual processing might operate through mechanisms partly independent of fronto-parietal networks that mediate voluntary spatial attention (Vuilleumier, 2002; Vuilleumier et al, 2002), but few imaging studies have examined whether processing of emotional auditory signals can similarly influence perception and attention (e.g. Jäncke Buchanan, Lutz, & Shah, 2001; Sander & Scheich, 2001; Grandjean et al., 2005).

Co-existing with these neural networks that process emotional signals independently of endogenously driven attention, other neural networks might differentially respond to emotion as a function of the current task relevance or selective attention. For instance, although the amygdala and fusiform cortex can activate to fearful faces without selective attention, regions in the medial prefrontal cortex and temporal poles show greater responses to task-relevant than to task-irrelevant fearful faces (Vuilleumier et al., 2001; see also Pessoa et al., 2002). Similarly, ERP data (Holmes, Vuilleumier, & Eimer, 2003) showed that emotional faces evoke a greater frontal positivity over the scalp when attended, as compared with neutral faces, but not when unattended. Taken together with the results obtained by Lane et al. (1997) and Gusnard et al. (2001) (see above, Section 2.3.1), these data are consistent with the view that the prefrontal cortex may control attention to emotional information (see Bush, Luu, & Posner, 2000; Compton, 2003). Thus, at least in the visual domain, some regions in the prefrontal cortex may respond during appraisal processes only when attention is selectively directed towards the emotional events (Vuilleumier et al., 2003). In the auditory domain, a recent study by Mitchell, Elliott, Barry, Cruttenden, and Woodruff (2003) also showed greater activation of the medial frontal gyrus when participants had to judge the emotional prosody of sentences relative to when they judged the verbal semantic content of the same stimuli.

In a recent experiment, Grandjean et al. (2005) used fMRI to measure neural network responses to emotional prosody during a dichotic listening paradigm. Participants were presented with meaningless but word-like utterances spoken with either angry or neutral prosody (see Banse & Scherer, 1996) simultaneously to the right or the left ear, respectively. Participants were requested to perform a gender decision task on the voices heard, either in the left or the right attended ear. Results demonstrated for the first time that anger heard in meaningless speech sounds evokes an increased neural activation in the middle portion of the superior temporal sulcus (STS), corresponding to one of the human brain areas previously reported to exhibit voice-selective responses (Belin, Zatorre, Lafaille, Ahad, & Pike, 2000). Crucially, this activation was independent of whether anger prosody was presented to the task-relevant or to the task-irrelevant ear. Furthermore, results showed that this response to anger in STS was distinct (i.e. additive) to a concomitant modulation of STS by voluntary attention when participants were selectively listening to emotional voices (relative to ignoring such voices), suggesting a separate source of these modulatory influences. Importantly, STS activation to anger is specific to auditory stimuli perceived as human voices, and not observed for synthesized sounds matched for fundamental frequency or amplitude envelope of the anger prosody stimuli but presented in isolation. These influences of emotion on voice processing in STS provide a striking parallel with similar enhancement found for the fusiform cortex in response to faces with fearful expressions (e.g. Vuilleumier et al., 2001). These findings suggest that emotion and attention can both exert separate modulatory influences on auditory processing, and they extend previous findings in the visual domain for fearful expressions in faces (Vuilleumier et al., 2001). Moreover, results of the dichotic-listening experiment also revealed an amygdala response to anger prosody—dissociated from any concomitant task-related attentional modulation (Sander et al., 2005). This finding is consistent with the notion that the amygdala may play a critical role in relevance detection, allowing efficient orienting of processing resources towards salient events. Although the activation of the amygdala was not very pronounced, this finding clearly parallels previous evidence obtained in the visual domain (e.g. Vuilleumier et al., 2001, 2004) and is relevant to current controversies on the nature and limits of automatic processing in the amygdala (Dolan & Vuilleumier, 2003; Pessoa & Ungerleider, 2004; Pourtois & Vuilleumier, in press; see also Taylor & Fragopanagos, in press). It still remains to be established whether the emotional effects in STS were driven by amygdala inputs, as shown for fusiform responses to fearful faces (Vuilleumier et al., 2004). The authors found that, in contrast to the attention-independent emotionally driven enhancement in the amygdala and right STS (Sander et al., 2005; see also Grandjean et al., 2005), for the very same pairs of stimuli containing an angry voice and a neutral voice, the orbitofrontal cortex and the cuneus in the medial occipital cortex were more activated when the angry voice was task-relevant than when it was task-irrelevant. Taken together, these results showed a functional dissociation between brain regions responding to emotional prosody independently of current task relevance (i.e. amygdala and middle STS) and brain regions differentially responding to the same emotional stimuli as a function of such task-relevance (i.e. orbitofrontal cortex and cuneus) and therefore support the proposal that multiple levels of processing are involved in the appraisal of emotional events (see Sander et al., submitted for publication).

In conclusion, both research strategies (‘bottom-up’ and ‘top-down’) represent interesting avenues to investigate the levels of processing in the appraising brain. These strategies are not mutually exclusive, each one revealing complementary properties of the neural networks. For example, experimental evidence suggests that the amygdala is both (1) sensitive to basic primitives of the emotional signal and (2) involved in the processing of emotional events that are task-irrelevant but self-relevant. Although the considerations presented here support the notion of multi-level processing of emotional stimuli, cognitive neuroscience research on the specific levels of processing suggested by appraisal theories would probably be even more beneficial to theories of emotion.

3. Towards computational models of appraisal and emotion

In a recent review of the CPM, Scherer (2001) has made a first attempt to sketch some of the features of a more formal model of the process mechanisms that may underlie the sequential check and componential patterning theories (see Fig. 3).

It is suggested that the bulk of appraisal processing occurs in an information-processing system similar to that described by Cowan (1988). The contents of the brief sensory storage (or sensory registers; see Karakas, 1997; Shiffrin & Atkinson, 1969) are processed or ‘coded’ by a range of procedures from simple pattern matching to logical inference, based on schemata and representations that are activated in long-term memory. Consistent with the conceptualization by Leventhal and Scherer (1987) and the multiple path model suggested by LeDoux (1996) (see Section 2 above), we assume that on a first pass, pertinent schemata are recruited in a largely automatic fashion to determine whether a satisfactory match (and, in consequence, a promising adaptational response) can be selected. In many cases, this is followed by controlled processing based on propositional content activated in long-term memory, giving rise to more elaborate evaluation and inference processes (see lower part of Fig. 3). We suggest that the results of both types of processing activate a *network of representational units* that corresponds to the appraised characteristics and significance of the event. The activation state of this representational network is constantly updated as the appraisal process unfolds. It is suggested that there is one node for each of the checks (as shown by the enlarged representation in Fig. 3). In parallel processing fashion, all checks will always be performed (this does not mean, however, that the content of the respective node will always have an impact on the adaptational response, i.e. the type of emotion that will ensue; see below). Given constant updating, each node will always correspond to the best available estimate of the respective aspect of the stimulus event that is currently processed. The representational network as a whole represents the overall significance of the event for the individual.

As suggested above, the SECs do the job of providing the four essential types of information required for action preparation: relevance, implication, coping, and normative significance. Given the presumed network architecture, the contents of the representational units corresponding to individual SECs are continuously integrated with respect to these classes of information. In Fig. 3, this is demonstrated by the connections between the SEC units and the boxes representing these information types. The specific integration for each of the information types will vary continuously as a function of information updating in

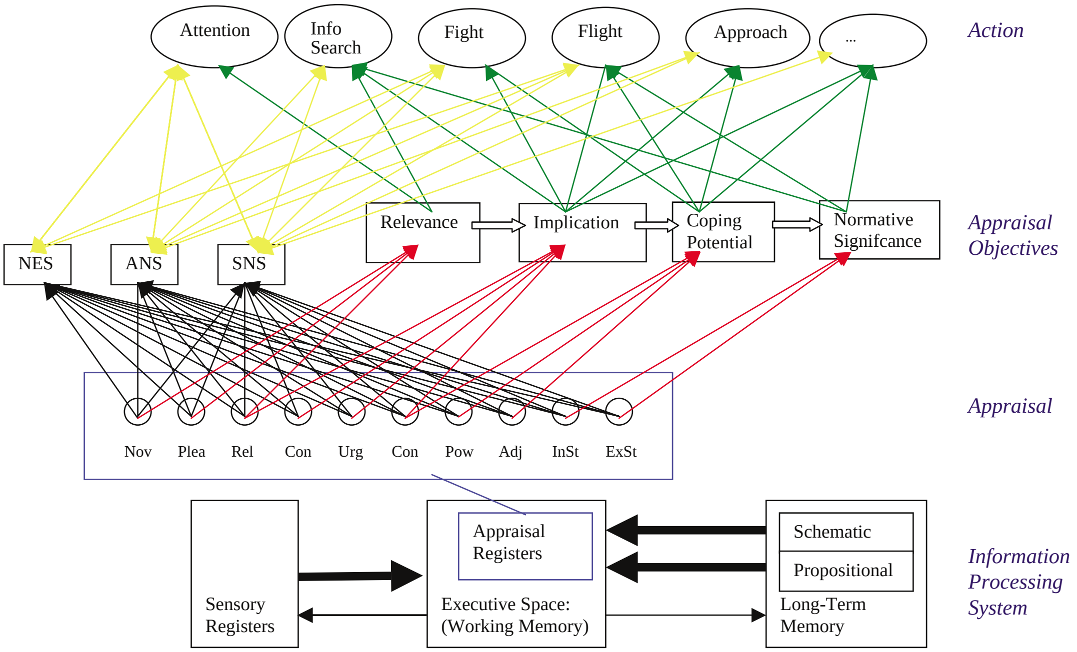

Fig. 3. Sketch of the potential architecture of the appraisal process as part of a general information processing system, separately driving peripheral support systems and alternative actions tendencies.

the network. It is expected that the different checks are integrated through weighting functions, giving them differential importance in the combination. These weighting functions may vary depending on the nature of the context (see Wehrle & Scherer, 2001).

A computational model reminiscent of a neural network architecture has been chosen for parts of Fig. 3 because it allows the graphical representation of the connections and activation patterns in the model. The assumption is that the profile of integrated information in the four major classes will activate potential response mechanisms (e.g. in the form of action tendencies; see Frijda & Zelenberg, 2001). A number of such action tendencies (as part of the executive subsystem) are shown in Fig. 3. As in a neural network model, one can assume that, depending on the profile of appraisal results, different action tendencies will be more or less strongly activated and will, in turn, activate the different parts of the support subsystem, the NES, the ANS, and the SNS. However, the current version of the model, as shown in Fig. 1 and represented in Fig. 3 by the connections between check units on the one hand and NES, ANS, and SNS on the other, assumes that there are direct connections of the SEC units with these response modalities, independently of action tendencies.

However, as mentioned above, it is assumed that such efferent effects will only occur if a minimal degree of closure (or definitiveness) of the evaluation of a specific check has been achieved (to avoid constant vacillation of the organism). The same is true for the level of integrated information where, as shown in Fig. 1, it is expected that there will be sequential ordering of the moments of closure. One possibility of envisaging the mechanism for achieving closure that warrants efferent effects is to postulate markers of confidence or certainty for the contents of the representational units, combined with the temporal persistence of the same informational content in the node (which indicates that there has been no updating and that the information is stable). Thus, the specific content of a node will only have an influence on response patterning (and thus on the type of emotion) if the content is considered sufficiently reliable. It is likely that there is an interaction between appraised urgency and the confidence or reliability required for efferent effects; in cases where action is seen as urgently required, efferent effects may occur even at lower levels of appraisal reliability or certainty.

Clearly, these suggestions need to be fleshed out in much greater detail to allow serious modeling and testing. However, it is important to underline that neural network models may well be especially suited to the type of modeling required for appraisal processes. In discussing the feasibility of modeling appraisal processes, authors such as Chwelos and Oatley (1994) and Spackman (2004) start from the mistaken assumption that simple hierarchical decision trees or rule systems are the only solution to computationally model the CPM (see Wehrle & Scherer, 1995, for a first critique of these problems). More recent models are also mostly based on rule systems and may suffer from similar problems (e.g. Gratch & Marsella, 2004; Staller & Petta, 1998, 2001). Advanced neural network models may be preferable in that they are better able to accommodate some of the specific architectural and procedural features of emotion. One such feature is the simultaneity of massively parallel processing with a sequential and cumulative decision and efference structure, as described above. As described early on by Minsky (1985), this type of architecture can be appropriately handled by hierarchical processing. This corresponds to the fact that many circuits are continuously active and emotional quality changes continuously because of changes in input, appraisal, and proprioceptive feedback. In consequence, any binary decision structure is completely inapplicable to the problem. A multi-layered outcome of the processing, as shown in Fig. 3, also corresponds to the presumption of the CPM (which seems to be confirmed by poets and artists) that there is an enormous richness and subtlety of different emotional qualities (the philosophers' *qualia*) rather than a shortlist of the 'big six' basic emotions as end points. Also, given the importance of multi-modal and temporal integration that was postulated above as one of the hallmarks of feeling, integration and weighting in the form of dynamically adaptive differential activation and inhibition thresholds might be more appropriate modeling principles as compared to fixed weights in regression or decision structures.

Most important, as briefly noted above, finding many linear transfer and integration functions for emotion, as simple linear regression models require (and as generally used in this research domain) is quite improbable. Rather, one can expect complex non-linear functions, often context bound. Scherer (2000) has suggested turning to dynamic linear systems, in particular chaos and catastrophe theory, to more appropriately model emotional dynamics. The essential arguments will be briefly summarized below.

Essentially, it has been argued that the synchronization of the subsystems constituting the emotion episode is driven by the results of the appraisal checks. Given the recursive nature of the system processes, the appraisal process is affected by prior changes in the different system components (see Fig. 1). For example, feedback of increasing arousal from the physiological system or changes in the motivational system can affect attention deployment or change perception and judgment thresholds.

As the various subsystems of the nervous system are characterized by highly variable response (attack and decay) and regulation characteristics, the components of the emotion process are unlikely to correlate in a direct, linear fashion. Rather, lagged covariation, non-linearity, differential damping, and many other aspects of complex synchronization are to be expected. This suggests that emotion episodes might be profitably considered as processes of self-organization among neurophysiological systems that are mapped into cultural meaning structures. More precisely, appraisal is expected to drive the synchronization of coupled neurophysiological oscillators in a process of entrainment by networks of CNS activity. Many of the non-linear dynamics characteristics described by self-organization theory, chaos theory, and catastrophe theory may help to develop models and measurement procedures for synchronization (for example, discreteness within continuity, order within chaos, simplicity within complexity, non-linear dynamics, emergence of structure, self-organization, complex coupling, synchronization, entrainment of subsystems, sensitivity to initial values, sudden change; see Glass, 1991; Gleick, 1987; Haken, 1991, Zeeman, 1976).

A central notion in this area is that of an *attractor,* implying that synchronized subsystems or oscillators are 'drawn into' or entrained to specific synchronized modes that have a tendency to be more stable than other, continuously changing states. Examples for such attractors in biological systems are oscillations of REM and NREM sleep driven by neural pacemakers (Mahowald, Schenk, & O'Connor, 1991), rhythm synchronization between respiration and cardiovascular parameters due to a mutual reinforcement of the coupling of the rhythmic activities in the different systems (Kaplan & Talajic, 1991) and differential degrees of coupling between these different systems in various syndromes of illness (Goldberger, Rigney, & West, 1990; Kaplan & Talajic, 1991). It has been suggested (Glass, 1991) that some forms of human diseases can be associated with bifurcations in the dynamics of physiological systems as a result of changes in control parameters. The notion of forced synchronizations in coupled systems in regulatory physiological systems can be extended to the role of psychological factors serving as drivers of underlying biological oscillators. For example, Redington and Reidbord (1992) suggest that a patient's cardiac responses associated with psychologically meaningful events in a psychotherapy session possess non-linear characteristics and may be indicative of chaos.

A particular form of synchronization of coupled oscillators, consisting of 'mutual' synchronization of interactive subsystems in the absence of a central pacemaker, seems directly applicable to the emotion architecture as outlined above (see Scherer, 2000, for a more detailed justification). Experimental research shows that in the case of mutual synchronization, many families of attractors exist and that the region of synchronization for each of these has its own boundaries (see Anishchenko, Vadivasova, Postnov, & Safonova 1992). This principle would seem to be directly applicable to the organization of the emotion system, as characterized by overlapping yet discrete modal states (Scherer, 1994).

One could object that this model might be applicable to physiological reactions in emotion but rather unsuitable for cognitive appraisal, expressive motor movement, or the verbalization of feeling state—all of which are considered components of emotion. However, by adopting a neurophysiological approach, one can view cognition as coupled oscillation of spatio-temporal CNS excitation and motor movement as coordinated efferent output to various muscle systems—again characterized by coupled oscillation. The basic idea is that conceptualizing the emotions as an increase in coupling or entrainment of several organismic oscillators, including the neurophysiological activities in the brain, might help us to finally study emotion as a process rather than as a state.

The dominant, functional view of the emotions sees their evolutionary origin in the facilitation of adaptation to emergency situations. This function can be nicely explained by conceptualizing emotions as attractor states of limited duration in the service of rapid adaptation to changed conditions. Thus, Haken (1991) suggested that physiological systems, in their normal functioning, are close to instability points, as this allows the system to adapt to new situations rapidly by transiting to more synchronized attractor states. As we shall see, this kind of system characteristic is ideally suited to modeling emotion processes. The underlying mechanism is nicely illustrated by the dynamic systems account of the processing of odor perception in the rabbit (Freeman, 1992; Skarda & Freeman, 1987). These authors start from the assumption that chaotic dynamics provide an essential interface between the infinite complexity of the environment and the finite capacity of the brain by its function as a finite dimensional pattern generator. The brain is seen as basing its selective action on its sensitivity to initial conditions and its ability to amplify microscopic events into macroscopic patterns that allow rapid adaptations to fast-changing environments (Freeman, 1992, p. 480). Freeman and his associates show that when the olfactory system is given a step input by an inhalation that excites the olfactory receptors in the nose, the olfactory bulb is excited by a surge of receptor firing. The olfactory bulb's response to this excitation can be shown by a slow wave in the EEG that accompanies inhalation. Superimposed on this respiration-based oscillation is a brief burst of oscillation near the characteristic frequency of the olfactory bulb. This burst is transmitted to coupled oscillators where this burst appears at the carrier frequency of the olfactory bulb (which serves as pacemaker). These bursts are interpreted as a destabilization of the basic chaotic state of the olfactory system, a phase transition to an attractor state. Most important, this process does not require continuous input from an external pacemaker. The carrier wave in the olfactory system is not imposed by external input; rather, it merges as a cooperative activity that is self-organized by the neural masses (Freeman, 1992, p. 468).

A similar architecture might underlie the emotion-driving appraisal in humans. Appraisal results serve as input to massively coupled psychophysiological oscillators that, upon triggering by this input, undergo a state transition from previously chaotic behavior and undergo synchronization through the process of increased coupling and mutual entrainment. As mentioned above, one would have to postulate that different patterns of appraisal results produce different sets of order parameters that 'push' the synchronization process into the direction of specific attractor states. The end of the emotion episode would be characterized by a steady weakening of the synchronization, a decrease in the degree of coupling of the component systems, and a transition back to a more or less chaotic state (or, in some cases, may be due to new appraisal input by an abrupt transition to a new attractor state).

A comment on the assumptions of causality implicit in the mechanisms suggested here may be in order. Appraisal is a process in time with constantly changing results and, in turn, constantly changing driving effects on subsystem synchronization (and, consequently, type of emotion). The assumption is that the specific appraisal profile that moves subsystem synchronization into an attractor space that characterizes a modal emotion episode is the end result (in terms of a time slice) of sequential information accumulation and refinement. Appraisal is seen as the initiator and driver of the synchronization process but also as being driven by it. As is usually the case in self-organizing systems, there is no simple, unidirectional sense of causality (see Lewis, 1996, in press, for an extensive discussion of such reciprocal effects). Furthermore, in the sense of Haken (1977), we have to conceive of a circular causality between the macro organization and the micro-elements of a system.

Scherer (2000) has suggested that a dynamic systems account of emotion can actually help to focus some of the questions concerning the intractable mysteries of subjective feeling and the role of consciousness. Starting with the assumption that feeling (as distinguished from 'emotion', of which it is only one component) is a reflection of all ongoing changes in the different organismic subsystems, it can be analyzed as qualitative change in a monitor system that reacts to a degree of coupling or synchronization of the subsystems surpassing normal baseline fluctuations (see Section 1 above). Speculatively, one might assume that this is also the point when unconscious reflections of component subsystem changes become conscious.

As briefly mentioned above, emotion states viewed as attractor basins of coupled oscillators must be mapped into meaning systems. Emotion *labels* are seen as a separate phenomenon, related to emotional communication and the representation of cultural knowledge structures. These processes cannot be understood in the sense of oscillating systems but require categorical approaches. Obviously, the results of categorization and labeling, once having occurred, can and will influence appraisal and emotional regulation, and thus constitute an important input to the synchronization process. One of the major issues for the future is to understand the relationship between continuous time series or oscillations, on the one hand, and more stable, discrete states amenable or accessible only through categorization, on the other. The notion of 'attractors'—describing relatively stable patterns of repeated coupled oscillations with similar characteristics—may be useful in the context of describing 'modal emotions' (Scherer, 1994).

A second illustration of the use of dynamic non-linear systems models draws from catastrophe theory (Flay, 1978; Maas & Molenaar, 1992; Stewart & Peregoy, 1983; Zeeman, 1976). Of particular interest to emotion theorists is the notion of *hysteresis*, which refers to a non-linear part

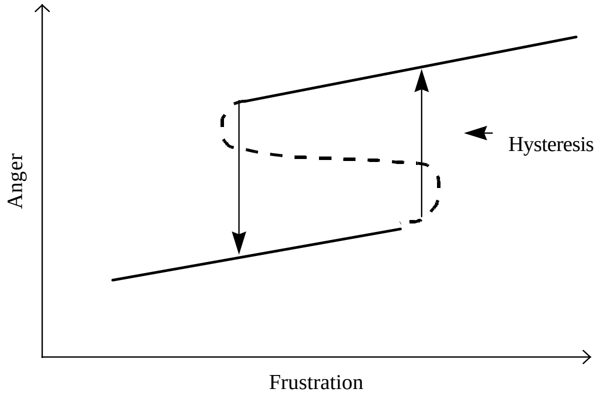

Fig. 4. An illustration of hysteresis in the frustration–anger relationship.

of a function that is inaccessible and that doubles back in its course. Take an example shown in Fig. 4. The figure plots the relationship between the degree of frustration and the anger elicited by it. Whereas a linear function would predict steadily rising anger with increasing frustration, a hysteresis function predicts that the intensity of anger will change abruptly for specific degrees of frustration. This explains two important phenomena: (1) the observation that with increasing frustration there may be a point where anger will, in a dramatic fashion, jump to a considerably higher level, a sudden flaring up of anger (see also Lakoff, 1987, on anger metaphors); and (2) the well-known fact that the point of departure may be an essential predictor for the development of an emotion. For example, if I start out with little frustration, and consequently little anger, there is a point where rising frustration will make my anger jump to a much higher level without going through any other intermediate stages. However, when starting from a high level of anger, produced by high frustration, and calming down because of a diminution of frustration, it is not at the same point as in the other direction that my anger will suddenly drop. Rather, it will take much less frustration before a drop to the lower level will occur. This is explained by partial overlapping due to the fold in the function.

The current conceptualization and modeling of emotion do not allow the prediction of the occurrence of such common emotional phenomena. Concepts like hysteresis are needed for modeling such effects, using more sophisticated mathematics and statistics than what is offered by standard analysis of variance or regression approaches, all of which are based on the assumption of linearity.

Hysteresis is also an essential feature of even the most complex catastrophe models, even though these contain more dimensions that need to be taken into account in predicting the underlying phenomenon. Zeeman (1976), one of the pioneers of the utilization of catastrophe theory in the social and behavioral sciences, provided a cogent example of the application of catastrophe theory to a classic behavioral phenomenon in ethology—the response conflict between attack and flight in a dog faced with an adversary with unknown strength (Lorenz, 1965), postulating a control space, which maps the dimensions or factors controlling the behavior of the animal and a response surface upon which the respective position of the animal in the control space is projected. The relative strength of the opposing tendencies to fight or flee represent the two orthogonal factors in the control space determining the respective position of the behavior on the response surface, and the change in behavior of the dog can be plotted as a path on the response surface (see Fig. 5). The presence of hysteresis in the form of a fold of the response surface helps to account for a number of well-known characteristics of emotional behavior, for example, abrupt changes from one moment to another as shown at the front edge of the fold. Furthermore, the fold in the behavior surface accounts for the fact that the change over time and the nature of the change in emotion processes will depend on the origin of the path.

Scherer (2000) has suggested that such catastrophe theory modeling can be profitably employed to model emotion responses as based on appraisal processes. Fig. 6 shows a two-dimensional model, as proposed by Zeeman (1976), which introduces two of the major dimensions postulated by all appraisal theorists into the control space: the goal conduciveness gradient (Factor A), characterized by the appraisal of the probability of reaching one's goal (to the left) or not reaching one's goal (to the right). Factor B, control or power, represents the appraisal of the degree of coping potential available to the organism to deal with a given situation (ranging from very little power toward the back to high power toward the front). Using the highly convergent predictions of appraisal theorists (see Scherer, 1999a, 1999b, 2001), one can project various positions of this two-dimensional control space onto the behavior or response surface and describe specific regions on this surface by emotion labels. Thus, as predicted by most appraisal theorists, anger is predicted to occur in conditions where the organism perceives a goal to be obstructed but considers having sufficient coping potential to deal with the block. What catastrophe modeling can add to the straightforward appraisal theoretical account is again due to the hysteresis fold in the behavior surface. Using the model, one can imagine how someone faced with adversity, i.e. seeing one's goal attainment increasingly threatened but perceiving a fairly high degree of coping potential or power, will move through states of hope and increasing determination to a point where a sudden switch to anger or even rage will occur. The fact that only a very small change in perceived obstructiveness and power needs to precede the sudden change is explained by the hysteresis fold in the behavior surface. Another example might be someone who appraises goal conduciveness as fairly low but increasingly evaluates coping potential to increase. This person moves from anxiety over resentment to a sudden change, due to hysteresis, to determination. Again, while the increment in perceived coping potential is relatively small, the change in the resulting emotion quality is quite dramatic.

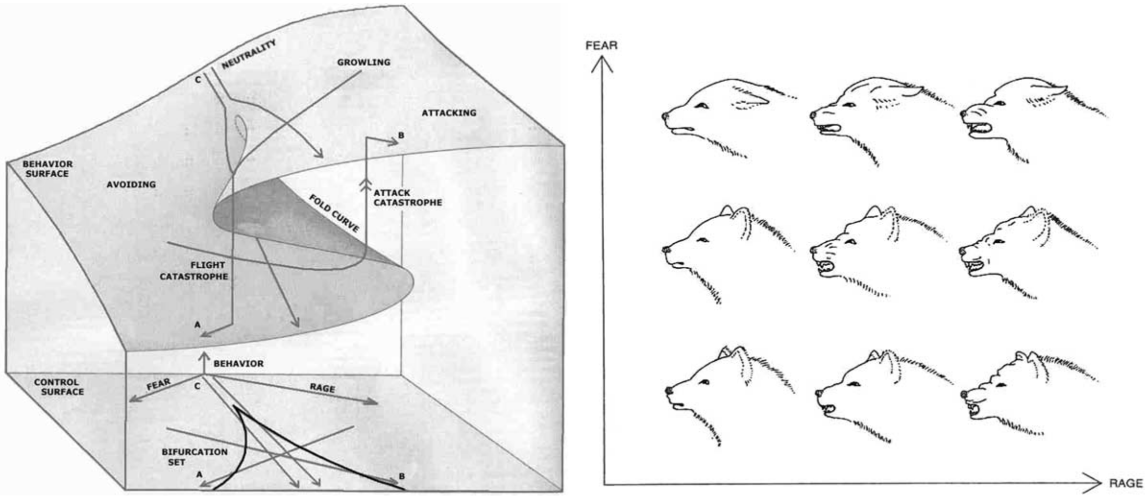

Fig. 5. Catastrophe modeling of the flight—attack dilemma in dog. Aggression in dogs can be described by a model based on one of the elementary catastrophes. The model assumes that aggressive behavior is controlled by two conflicting factors, rage and fear, which are plotted as axes on a horizontal plane—the control surface (see right panel). Control factors in the model of aggression are rage and fear, which in dogs can be measured by facial expression. The behavioral expressions as projected onto the behavioral plane are shown in the left panel, showing mixtures of the two control factors. Rage is reflected by the extent to which the mouth is opened, and fear is revealed by the degree to which the ears are flattened back. From these indicators, it is possible to judge the dog's emotional state, and through the model to predict its behavior (adapted from Zeeman, 1976).

Appraisal theorists postulate many more than two underlying control factors and the locations of the emotion labels on the behavior surface are in consequence quite approximate. In order to model additional control factors, one needs to move to complex, higher order catastrophe models, as described by René Thom and other catastrophe theorists (Stewart & Peregoy, 1983; Thom, 1982; Zeeman, 1976). Obviously, the introduction of higher order bifurcation sets in several dimensions allows an enormous variety of outcomes based on a fairly simple control structure. Modeling the dynamic processes involved in the sequence of appraisal changes in this fashion may help appraisal theory to move beyond a rather static prediction of semantic meaning of particularly emotional terms to a more dynamic approach, highlighting the changes that will occur upon incremental changes of the appraisal on particular dimensions. Most important, the effects of these changes may be non-linear. In other words, depending on the region involved and on the combination of the underlying appraisal dimensions, relatively small changes may produce dramatic consequences. Obviously, an empirical investigation of theoretical models of this sort requires a much finer measurement of the appraisal dimensions (for example, the use of interval scales) as well as a process measurement of appraisal in time (see Edwards, 1998) rather than retrospective one-point measurement, as has been the case in most appraisal research to date. This is an example of how modeling based on catastrophe theory can guide theoretical and empirical development in one of the central areas of current emotion research. In addition, such modeling promises to do a better job in explaining a number of intuitively obvious characteristics of emotional responses (such as abrupt changes that are difficult to explain by linear functions or dependency of the response on the origin or departure point).

The non-linear dynamic approaches described earlier complement the catastrophe modeling as described above. For example, the regions labeled by emotion terms on the response surface in Fig. 6 can be seen as attractors with auto-organizational properties. Thus, attractor spaces on the surface represent multi-dimensional vectors that are differentially affected by changes in the control structure. As mentioned above, the coupling of a normally independent oscillating system is explained by the need for adaptation that results from certain appraisals (represented as positions in the underlying control space in the model). Thus, it is the current state of the control structure that couples the independent

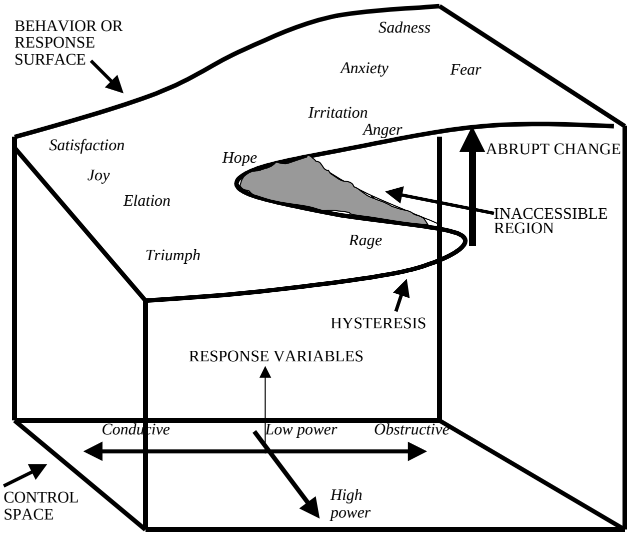

Fig. 6. A preliminary catastrophe model of appraisal.

oscillators. Of course, changes of the position in the control space must also explain the decoupling of oscillators underlying the travelling of the organism along a path on the response surface over time. However, most physical and biological systems have some degree of inertness built in, requiring a relaxation of prior constraints over some period of time before uncoupling can occur. This characteristic explains the existence of attractors that maintain the persistence of a particular state for some time.

4. Conclusion

So far, no neural network based computational model of the CPM exists. Scherer (1995) used the IAC shell provided by McClelland and Rumelhart (1988) to examine whether a neural network approach could be useful in understanding the elicitation and differentiation of emotion via cognitive appraisal processes. The program (available by writing to the authors) uses the predictions made by the Stimulus Evaluation Check (SEC) model (see Scherer, 1984, 2001) as the basis for the matrix of activation and inhibition patterns in the IAC shell, allowing to set inputs that correspond to the result of specific stimulus evaluation checks and generates activation patterns of hidden units and corresponding output patterns with respect to a number of discrete emotion labels. Setting the input patterns according to the theoretical predictions (i.e. Table 2 in Scherer, 1986, p. 147), the program produces results that correspond to the hypotheses. This is not surprising but confirms the internal consistency of the model. Apart from checking these predictions, the program allows to generate insights that are not predicted, such as testing the effect of setting the inputs sequentially rather than simultaneously, having the system run through several cycles before successive inputs, and comparing the differences in output between sequential and parallel processing (see discussion in Scherer, 1993). Furthermore, systematically varying patterns of input strength, or input profiles that deviate more or less from the predicted, prototypical profiles provide interesting insights and intuitions. Another issue of interest is the effect of partial inputs on those inputs that have not been activated, indicating interesting interactions between appraisal dimensions. Even this simple demonstration of the interaction of different appraisal dimensions to generate emotion categories or labels on a purely symbolic, categorical level produces interesting challenges for theoretical consideration and ideas for experimental manipulation. Clearly, a more formal attempt to computationally model, using current sophisticated tools, the CPM, including constraints imposed by what is known by the neural architecture and modeling the dynamic flow of recursive effects, is likely to yield results of major importance for the further development of theorizing and research in emotion. Thus, it is hoped that the existence of a theoretical model that encourages neural network modeling will motivate scholars in this area to invest in this hitherto neglected domain. Together with the ever accelerating increase in both the sophistication of research methods and the resulting understanding of the neural architecture and the dynamic processing underlying our cognitive and affective performances and experiences, the time may be ripe to venture into more complex levels of neural network modeling, including dynamical systems approaches (Taylor, 1992).

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