EMA: A process model of appraisal dynamics

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Abstract

A computational model of emotion must explain both the rapid dynamics of some emotional reactions as well as the slower responses that follow deliberation. This is often addressed by positing multiple levels of appraisal processes such as fast pattern directed vs. slower deliberative appraisals. In our view, this confuses appraisal with inference. Rather, we argue for a single and automatic appraisal process that operates over a person's interpretation of their relationship to the environment. Dynamics arise from perceptual and inferential processes operating on this interpretation (including deliberative and reactive processes). This article discusses current developments in a computational model of emotion processes and illustrates how a single-level model of appraisal obviates a multi-level approach within the context of modeling a naturalistic emotional situation.
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1. Introduction

Change is an inherent quality of emotion. Aroused by an unpleasant event, a person might explode into anger, then fume at a slow boil, and finally collapse into sadness. Once aroused, emotions influence our actions and judgments concerning the event, altering what Lazarus (1991) calls the person–environment relationship. Changes to this relationship may induce new emotional responses, resulting in a cycle of change in the person's relation to the environment. These changes can be rapid, on the order of milliseconds, or unfold over days and weeks. In short, emotions are inherently dynamic, linked to both the world's dynamics and the dynamics of the individual's physiological, cognitive and behavioral processes.

A key challenge for any theory of emotion is to explain this dynamic emotional process. Over the last 50 years appraisal theories have become the leading theories of emotion. These theories posit that emotion arises from a person's interpretation of their relationship with the environment. This interpretation is mediated by cognitive processes and can be described by a set of *appraisal variables* (e.g., is this event *desirable,* who *caused* it, what *power* do I have over its unfolding).

Appraisal theories have largely focused on structural considerations such as specifying the dimensions of appraisal and the appraisal patterns characteristic for different emotions. In order for appraisal to model the dynamics of emotion, however, we must move beyond structural models to a model of the appraisal process (see Reisenzein, 2001 for discussion of this process-structural distinction). For example, Smith and Lazarus (1990) proposed a cyclical process between appraisal, coping and re-appraisal to explain how emotional responses unfold over time. However, this explanation of emotion dynamics, as well as appraisal theory in general, has been criticized as unable to account for the fact that emotional responses are often rapid and seemingly automatic (see Zajonc, 1980).

To address this concern, several researchers have proposed multiple appraisal processes operating on different

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timescales and with different levels of sophistication. For example, some appraisal researchers have postulated two-process models involving fast and automatic vs. slow and deliberate appraisals In this vein, Smith and Kirby (2000) argue for a two-process model of appraisal whereby *associative processing* (a memory-based process) and *reasoning* (a slower and more deliberative process) operate in parallel (see also Moors, De Houwer, Hermans, & Eelen, 2005; Reisenzein, 2001). Scherer proposes an even more involved scheme with multiple levels of processing and sequential constraints within each level (Scherer, 2001).

In our view, these multi-level theories of appraisal unnecessarily complicate appraisal processes by conflating *appraisal* and *inference*. Rather, we argue that appraisal and inference are distinct processes that operate over the same mental representation of a person's relationship to their environment. We distinguish between the construction of this representation, which may be slow and sequential, and its appraisal, which is fast, parallel and automatic. Differences in the temporal course of emotion dynamics are accordingly due to differences in the temporal course of the perceptual and inferential processes that construct this representation (including both deliberative and reactive processes). This allows the model to explain both fast, seemingly automatic emotion responses as well as slower, seemingly more deliberative responses, without recourse to a more complicated multi-level model of appraisal.

However, to address fully the question of the processes that underlie appraisal, we must go beyond such abstract descriptions to detail the processes by which the values of the different appraisal variables are determined. Additionally, the basic mapping from appraisals to emotions of specific type, intensity and durations must be specified. Completing the cycle, the impact of emotions on coping responses and subsequent changes in the person-environment relationship must be detailed.

More generally, we see the computational modeling of emotions as a powerful approach to address the question of the processes that underlie appraisal. The construction of a computational model forces specific commitments about how the person–environment relationship is represented, how appraisals are computed on the basis of these representations, about the role of perception, memory, interpretation and inference in appraisal, and about the relationship between appraisals, emotions and coping responses. Often these commitments raise issues that are unforeseen at the level of more abstract specifications of a theory. Further, once computationally realized, simulation allows the model to be systematically explored and manipulated, thereby generating predictions that can be tested by comparing them to the reactions of human subjects. Indeed, computer simulations may be the only feasible approach to uncover the increasingly subtle consequences of competing theories of appraisal processes.

This paper advocates a particular theoretical stance towards the problem of capturing emotional dynamic that is informed both by the appraisal theory of Smith and Lazarus (1990) and our experience in realizing this theory in a computational process model called EMA – for EMotion and Adaptation (Gratch & Marsella, 2004a; Gratch & Marsella, 2005; Marsella & Gratch, 2003). In this paper, we seek to achieve two goals. First, we provide an updated description of the EMA model, incorporating both recent developments in the model as well as clarifying how EMA's single-level model of appraisal obviates a multi-level approach. Second, we illustrate our theoretical approach by modeling a naturalistic emotional situation in EMA that involves both rapid and slower emotional responses.

1.1. An example of emotion dynamics

In our view, a key criterion for evaluating a model of emotion concerns its "process validity": Does the model capture the unfolding dynamics of emotions? One way to perform such an evaluation is to compare the model's behavior to human data obtained by assessing emotional responses, appraisal variables and coping tendencies in an evolving emotional situation. In previous work, we demonstrated how the EMA model (Gratch & Marsella, 2005) was consistent with subjective report data of human subjects imagining how they would respond to a *slowly* evolving situations (from Perrez & Reicherts, 1992). However, a more significant challenge to a process model of appraisal is to explain evocative situations people's reactions to situations that elicit a wide array of emotional responses in a short time period.

To begin to address that challenge, we have analyzed and modeled a naturalistic emotion-invoking situation, recorded during one of our lab studies. We were videotaping actors at 30 frames per second as part of a study on gestures and postures. In the midst of instructing the actors, a pigeon unexpectedly flew in through the window. Fig. 1 has several frames of the video that reveal key points in the visible reactions of one of the two actors (due to space considerations not all frames mentioned in the text are shown). Although such an unexpected, uncontrolled event makes a rigorous analysis difficult, it serves well to illustrate the rapid dynamics of emotion that we would want to explain by our computational process model of appraisal. Our goal is not to definitively explain or reconstruct the actual inferences and emotions experienced by this particular actor, but rather to illustrate how such dynamic situations could be modeled by a process model of appraisal.

In the video, the actor holding the umbrella goes through a sequence of behaviors that suggest the following *interpretation*:

- surprise at an unexpected event (frame 5),
- fear (frame 9),
- an aggressive stance of self-protection (frames 13–23),
- relaxation (frame 29),
- concern for others (frames 29–60), specifically for the bird that caused the initial negative reaction and, finally,
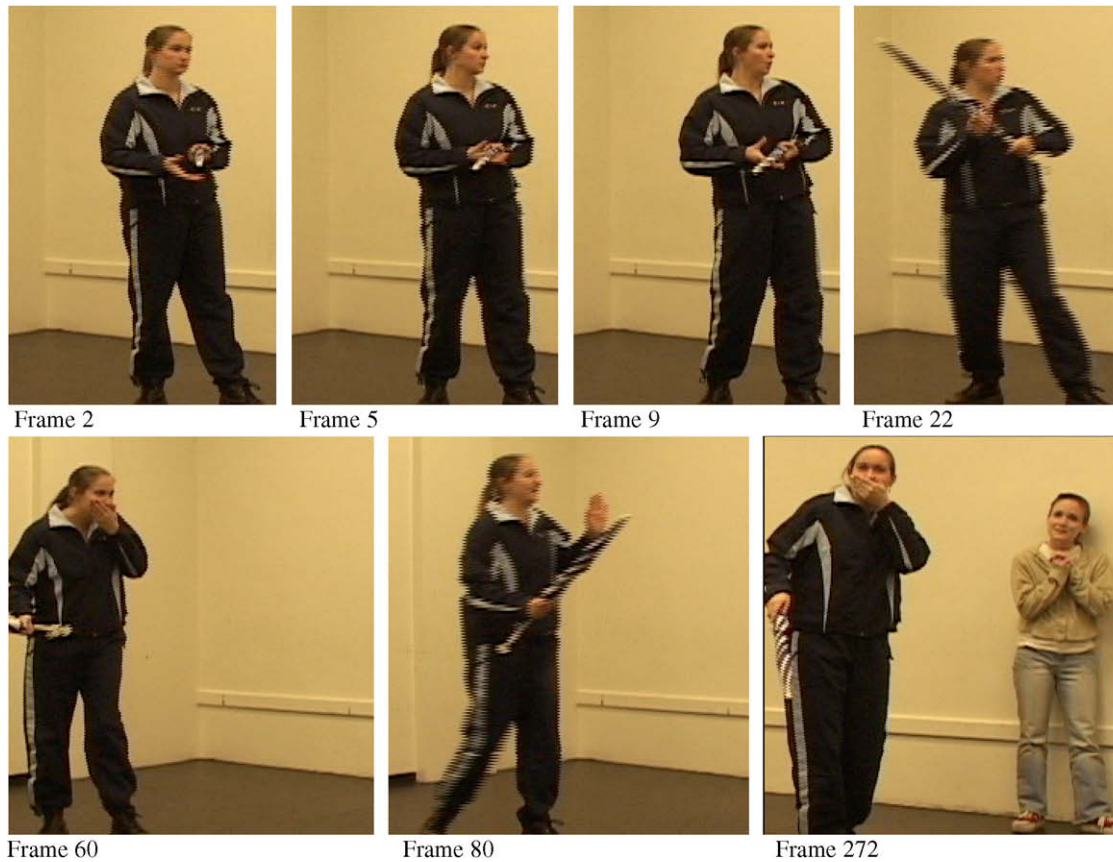
Fig. 1. An illustration of the dynamics of emotional expressions taken from 2.6 seconds of video.

- an active helping strategy (frames 62–80) combined with relaxed facial features and smiling suggestive of relief.

The sequence of behaviors that suggest this interpretation is as follows. By frame 2 (F2), the actor has begun to turn and orient toward the sound of the bird. Her eyebrows rise (F3–F5). The eyebrows return to a more neutral level and the mouth begins to open by F8. The Eyebrows lower and the jaw then drops during F11 and F12. In F13, she begins to grab the umbrella at the base, move the left foot back away from bird and starts to raise arms. She raises the umbrella (F14–F22), shifting her weight to her right, rear foot away from the bird. Her posture and grasp of the umbrella suggests she is prepared to ward off a presumed attack of the bird by whacking it with the umbrella. She continues her backward motion. Her motions slow and by F29 her left hand starts to let go of the umbrella and move towards her mouth. The umbrella is lowered in F34 and her left hand covers her mouth by frame F42. By F62 the backward motion stops (she moves approximately 6 feet) and the left hand begins to lower from covering her mouth. By F66, the actor begins to move forward and the hand lowers sufficiently to reveal relaxed facial features. In F72 through F80, the forward motion continues, the hand forms into a stop gesture and the face appears to be smiling (laughter and utterances expressing concern for the bird are also heard).

A seemingly identical sequence of reactions is visible in the other actor: raised eyebrows, lowered eyebrows and jaw drop, followed by expressions suggesting relief/amusement and compassion. But reactions also differ, for she becomes aware of the bird later, she is closer to the threat and certain responses are not facilitated by the instrumentality of the umbrella.

This rapid transition in the actor's expressive state and behaviors lasts only 2.6 s. The expression of raised eyebrows often associated with surprise takes on the order of 30–60 ms and the expression of lowered eyebrows and lowered jaw often associated with anger and responses to threat takes about 300 ms. Overall, the observed reactions suggest a progression from surprise about the unexpected event, concern for personal significance, and finally concern for others. Tightly coupled with these evolving concerns from threat-to-self to threat-to-other, and the emotion dynamics of fear/anger to compassion/relief, is a corresponding progression of coping responses from defend/attack to help.

1.2. Sources of dynamics

In analyzing the bird example, several factors can help us explain its dynamics. Perceptual and inferential processes alter the actor's interpretation of the situation. These inferential processes have internal dynamics, requiring time

to draw initial inferences and those inferences may evolve as more knowledge is brought to bear on the problem. Furthermore, the situation itself changes. This is in part due to events external to the actor such as the bird flying in the window, flying toward the actor, etc. as well as to the actor's own actions or coping responses. These responses may directly transform the situation by affecting the world, such as "arming oneself" and moving away from the event, or they may alter the actor's beliefs and intentions (what Lazarus called emotion-directed coping responses). These situational or cognitive changes in turn may lead to re-appraisals of the situation. The processes of devising and executing a coping response or plan to deal with the event have their own temporal dynamics and, as part of these responses, other aspects of the situation may become the actor's focus of attention (such as the threat to the bird).

In addition, different theories of appraisal posit sources of dynamics grounded in the appraisal process itself, involving such factors as the inferential demands that underlie an appraisal and/or potential logical ordering relations between different appraisal steps.

We turn now to how alternative theories of appraisal might explain the response dynamics we see in the bird scenario.

1.3. Alternative explanations of the dynamics

Process models of appraisal have often sought to explain the rapid versus slow emotion responses by positing multiple levels of appraisal that encompass both slow and fast appraisal processes. Here we discuss two of these models, Scherer's (2001) multi-level sequential check model and Smith and Kirby's (2000) two-process model.

Scherer's multi-level sequential check model posits three levels of appraisal processing, innate (sensory-motor), learned (schema-based) and deliberative (conceptual). In addition, the model posits sequential ordering of appraisals, specifically that "there is a definite, invariant order in which the different stimulus evaluation checks are processed." Scherer bases this view of sequential processing in appraisal on "phylogenetic/comparative, ontogenetic, physiological, and functional considerations." Of particular interest, Scherer argues that "in terms of economy it seems useful to engage in expensive information processing only upon detection of a stimulus that is considered relevant for the organism" and consequentially requires attention. For example, "causes and implications need to be established before the organism's copping potential can be conclusively determined since the later is always evaluated with respect to a specific demand. [Only] once this information is in, the overall significance of an event ... for the self and its normative/moral status can be evaluated".

The ordering of appraisals in Scherer's model provides one explanation of the evolution of emotional responses seen in the bird video. The model argues the relevance check precedes implication check, implication precedes the coping potential check and coping potential precedes the check for normative significance. The relevance check includes assessment of novelty as well as relevance to one's goals. The implication check includes assessments of cause, goal conduciveness and urgency. Coping potential includes assessments of control (whether the situation is controllable) and power (whether the individual has the power to control it). Finally, normative significance includes assessments of compatibility with internal and external standards.

A correspondence between the ordering of these appraisal checks and the interpretation of the sequence of behavioral reactions seen in the bird video can be set up as follows. The relevance check corresponds to surprise (Frame 5). Implication check corresponds to fear (Frame 9). Coping potential corresponds to the adoption of an aggressive stance (Frames 13–23). Normative significance corresponds to the concern for others, specifically the bird (Frames 60, 80 and 272).

Smith and Kirby's two-process model of appraisal distinguishes between slow appraisals based on more or less extensive reasoning from fast appraisals that are associative or memory-based. These slow and fast appraisal processes work in parallel and are integrated to arrive at overall appraisal of an event.

This two-process model presents an alternative explanation of the bird scenario. The initial response of the actor that suggests surprise (Frame 5) could be the result of a fast appraisal process. On the other hand, the expression that suggests concern for others might be the result of the slow appraisal process. The intermediate responses that suggest fear and anger may be some blend or integration of fast and slow appraisals.

In contrast to these multi-process models, we argue with the EMA model that appraisal is best seen as a fast, single-level of appraisal that can flexibly utilize the output of a variety of perceptual and inferential cognitive processes, some slow and deliberate and some fast and automatic. As a consequence, appraisal dynamics are essentially dictated by the time course of whatever cognitive processes are involved in interpreting and responding to an event: Appraisal results evolve as cognitive processes update the person-environment relationship.

Further, we argue that appraisal checks operate in parallel, and any apparent sequential relationship between appraisals is dictated by the processing requirements of the cognitive processes involved in constructing the representation of the specific appraisal-eliciting event, in contrast to the sequential checking of Scherer's model.

We agree with Scherer's view that appraisal checks have a typical order. However, we differ from Scherer with respect to the question of whether this order is invariant and the underlying cause of the order. The position we take in EMA is that appraisal checks operate in parallel and the apparent ordering of checks is a by-product of how the agent's subjective interpretation of the person–environ-

ment relation evolves as cognitive processes operate on the representation of this relation and thereby provide evolving information to the appraisal processes. Furthermore, Scherer's sequential checking hypothesis, by assuming that some appraisals require potentially heavy-weight inferential processes, suggests an invariance in the speed of emotional responses or at least an impact on the speed of those emotional responses that depend on these appraisals. Again, the position we take is that appraisal checks are uniformly lightweight, fast and operating in parallel. These fast appraisal checks operate on results from other cognitive processes that can involve either slow, involving extensive inferences, or fast, involving memory retrieval. By assuming various cognitive processes to generate results in a uniform representation scheme amenable to appraisal, appraisal itself is rapid and can evolve as cognitive processes update the person–environment relationship.

Note that these models postulate multiple processes, either multiple types of appraisal processes in the case of multi-level sequential checking and the two-process models, or a single-level of appraisal that leverages other cognitive processes, in the case of EMA. This raises a serious methodological concern. A process model that assumes multiple interacting sub-processes is difficult to falsify. Through variation in assumptions about how the processes interact, the model can be made consistent with the time course of emotions in any specific scenario. For example, in the case of multi-level sequential checking, altering at what level the various checks happen could alter the ordering of checks. For the two-process model, by adjusting which appraisals happen via the slow or fast processes, similar adjustments to the ordering of appraisal checks are feasible. In this article, we do not have an answer on how to resolve this issue. However, we believe a step in that direction is to develop models that detail how processes interact, including not only appraisal processes but also other cognitive and perceptual processes that may inform and influence appraisals.

To that end, it is important to distinguish between models that characterize appraisal processes in an abstract way (i.e., which postulate that certain appraisal processes are involved in emotion, and are evoked in a certain sequence) versus models that can tie emotional responses to the specific beliefs and inferences that might plausibly occur in a particular situation. For example, Sander, Grandjean, and Scherer (2005) propose an abstract neural network model that characterizes general information processing constraints but does not allow one to represent specific emotional situations. In contrast, our computational model of appraisal is designed to support the modeling of specific emotional episodes, such as the above bird scenario. Developing a model that can express such specific scenarios forces one to be very explicit concerning how such situations are represented, and how the various cognitive and appraisal processes operate on these representations and interact with each other. We discuss these issues in more detail in the following section.

2. Toward a computational model of appraisal processes

In our view, a computational model of emotion must explain both the rapid dynamics of some emotional reactions as well as the slower evolution of emotional responses that may follow deliberation and inference. In addition, the model should address how emotions arise and evolve over a range of eliciting situations ranging from simple physical events to complex social situations. Appraisal theories explain these phenomena abstractly in terms of underlying appraisal processes; that is, mechanisms that assess the immediate relevance of events for the individual, infer its implications or consequences to longer-term goals, and assess the individual's ability to adjust to or cope with these consequences.

Two problems immediately confront the computational modeler who wants to translate appraisal theory into a working computational model of appraisal processes. On the one hand, as is the case for most psychological theories, appraisal theory is not specified at a level of detail necessary to design a computational system: Although the theory implies certain process and representational requirements that any computational model must satisfy, there is still considerable freedom in how these requirements are concretely realized. On the other hand, individual appraisal theories differ from each other in a number of aspects, particularly with respect to their process assumptions (if such are made), and how these relate to emotion dynamics. In this section, we first lay out our the theoretical and process assumptions that inform our approach towards the computational modeling of emotions, then describe the current incarnation EMA, a general computational framework for modeling emotion (including previously unpublished details and recent developments in sufficient detail to provide a detailed analysis of this concrete real-life example of emotional dynamics (in Section 3).

2.1. Theoretical requirements

In our computational model of dynamic emotional processes, we adopt the central tenets shared by appraisal theories of emotion: Appraisal is a process of interpreting a person's relationship with their environment; this interpretation can be characterized in terms of a set of criteria (variously called appraisal dimensions, appraisal variables or appraisal checks); and specific emotions are associated with certain configurations of these criteria. In addition, appraisal theories posit specific appraisal dimensions and coping strategies that impose representational and inferential requirements on any system that hopes to accurately model the computation of these appraisals, as well as their consequences on cognition and behavior. Following Smith and Lazarus (1990), we argue that certain inferences are minimally necessary to distinguish between emotions (similar

distinctions are posited in a wide range of appraisal theories)[1]:

- *Relevance, valence and intensity*: Appraisal theories assume that emotions are associated with the detection and assessment of events of personal significance. This involves detecting events (which may be physical or mental), as well as assessing the direction (positive or negative) and the intensity (importance) of their impact. This means a computational model must represent events, actions and their immediate consequences, as well as the valence and intensity of these consequences for the agent.
- *Future implications*: Some emotions are about things to come (hopes and fears) or are reactions to expectation violations (e.g., surprise, disappointment). Appraisal theories argue that specific appraisal variables assess the likelihood, unexpectedness and changeability of events and their congruence with the agent's future goals. A computational model, accordingly, must represent future goals and expectations and must include mechanisms for assessing the likelihood of events and actions and their consequences, including interactions between possible outcomes (e.g., does achieving one goal interfere with achieving another).
- *Blame and responsibility*: Appraisal theorists assume that a first step in preparing a response to an emotion-evoking event is often to identify its cause, and specifically the agent responsible for its occurrence. Unlike causal reasoning in artificial intelligence, appraisal theories argue that causal attribution and the ascription of responsibility may involve the consideration of a variety of factors, including other actors' intentions (did they intend to hurt me?) as well as third agents (was the other actor coerced?). To make assignments of blame or credit, the model must represent some notion of causality and agency, as well as other actors' motivational and epistemic states such as intention and foreknowledge.
- *Power and coping potential*: According to many appraisal theories, an important determinant of people's emotional response is their subjective sense of control over the emotion-eliciting event. To reason about individual power, a computational model of emotion must therefore represent the extent to which events can be controlled (e.g., how robust is my plan?). To reason about social power, the model must have some representation of coercive relationships between agents such as representing different agents' spheres of influence or organizational hierarchies. In addition, appraisal theories consider not only the individual's external power (over

the world and other individuals) but also his or her internal power (e.g., one's ability to abandon a cherished goal or overturn a preconception). To reason about adaptability and to support so-called emotion-focused coping strategies, the model must be open to subjective reinterpretation (e.g., represent subjective rather than "true" beliefs).
- *Coping strategies*: Patterns of appraisal elicit emotional behavior, but they can also trigger cognitive responses referred to as coping strategies. These cognitive responses are hypothesized to act on a person's relationship to the environment by either changing the environment or a person's representation (e.g., plans, beliefs, desires or intentions). These include "problem focused" strategies (e.g., planning) directed towards improving the world (the traditional concern of AI techniques) but also encompass "emotion-focused" strategies that influence an agent's epistemic or motivational states. Because these coping strategies impact subsequent appraisals, they are tied closely to the evolving dynamics of emotion responses. A computational model must thus provide mechanisms for translating patterns of appraisal into appropriate external actions or changes to the current configuration of beliefs, desires, intentions and plans.

2.2. Process assumptions

In concretizing appraisal theory into a computational model, we adopt a number of specific process assumptions to confront ambiguities within the basic theory and to resolve the conflicting views of individual appraisal theorists.

Appraisal causes emotion: Theorists differ as to whether appraisal should be seen as the cause of emotion, a component of emotion, or even as identical to the emotion (see Barrett, 2006; Ellsworth & Scherer, 2003; James, 1884). Most appraisal theorists assume appraisals cause emotional responses – indeed, Frijda referred to this assumption as the *law of situated meaning* (Frijda, 1988) – and this view is also adopted in most computational models of emotion (Elliott, 1992; Hudlicka, 2005; Moffat & Frijda, 1995; Neal Reilly, 1996; Paiva, Dias, & Aylett, 2005; Scheutz & Sloman, 2001). EMA likewise incorporates the assumption that appraisal processes are the cause of emotional responses, although we also allow incidental influences on emotional state through a simple notion of mood (see Section 2.3.4).

Cycle of appraisal and re-appraisal: Appraisal theories also differ in their assumptions about how appraisals change and unfold over time. In fact, many appraisal theories do not explicitly address the question of appraisal and emotion dynamics (e.g., Ortony, Clore, & Collins, 1988), focusing, rather on the categorization of emotional responses in terms of different appraisal dimensions. Those appraisal theorists who do consider questions of dynamics

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[1] Appraisal researchers disagree on the full set of appraisal dimensions based on empirical or theoretical considerations. Placing appraisal theory within the context of a computational system invites us to make distinctions based on *architectural* considerations (e.g., how parsimonious are they with respect to the process assumptions of a specific cognitive architecture). We will revisit this point in the conclusion.

typically regard the person's coping response as central to explaining the dynamics of appraisal and emotional responses (e.g., Lazarus, 1991) and Ellsworth (1991). Following these theorists, we assume a cyclical relationship between appraisal, coping and re-appraisal. A person's initial appraisals of a situation provokes a variety of cognitive and behavior responses (e.g., they recruit physiological resources and initiate external behaviors) that change the person's relationship to the environment. The resulting cycle of appraisal and reappraisal is a central element in explaining the dynamics of emotion.

Appraisal is shallow and quick: Even though many appraisal theories do not explicitly speak to appraisal dynamics, most are consistent with Lazarus and Ellsworth's view of cyclical appraisal and re-appraisal as the overarching explanation for (typically longer term) emotional dynamics. However, as already mentioned in the introduction, and as further discussed in Sections 1.3 and 2, some appraisal theories go further, arguing e.g., for a distinction between automatic and nonautomatic appraisals that presumably underlies the short- versus long-term dynamics of emotional reactions. The reactions to the bird (Fig. 1) would most likely be regarded by these theorists as an example of short-term dynamics presumably based on automatic appraisal. However, in our view, arguments between short- and long-term patterning of appraisal confound appraisal processes with other cognitive processes. In contrast, we propose a clean distinction between inference (i.e., the cognitive processes studied in traditional cognitive science and cognitive modeling research) and appraisal, which we conceptualize as comparatively simple evaluations of the results of inference processes. Specifically, we argue that appraisal processes are always fast (reactive), parallel (in the sense of Moors et al., 2005) and unique in the sense that we postulate a single-level process. However, multiple other processes, both perceptual and cognitive, perform inferences (both fast and slow, both deliberative and reactive) over the representation of the person–environment relationship. As those inference processes change the interpretation, they *indirectly* trigger automatic reappraisal.

Fig. 2 graphically illustrates the relations we assume to exist between appraisal, emotion, coping and cognitive processes and illustrates the three key sources of emotional dynamics in our model. Based on the framework outlined by Smith and Lazarus (1990), our model assumes that a representation of the "agent–environment relationship" is continuously updated. Furthermore, we assume that the represented agent–environment relationship is appraised, continuously and automatically, resulting in emotional and coping responses. Critical to emotion's role as an interrupt and attention-focusing mechanism (Simon, 1967), we envision that this automatic appraisal operates over the entire contents of working memory. Inference, including the agent's planning, belief revision and perceptual processes, update the agent's representation of the agent–environment relationship. The agent's actions also change the world, which in turn influences the agent's relationship with its environment. Both action execution and inference are influenced by coping responses, thereby establishing an appraisal → coping → reappraisal loop. In addition, of course, the world may change dynamically without agent intervention, due to other agents taking actions, as well as natural events and processes.

To concretely realize the dynamic unfolding of emotional responses over time through the tightly coupled interaction of cognition, appraisal and coping, a computational process model must explicitly represent intermediate knowledge states, that may be appraised, augmented by further inference, and transformed by coping responses. Critically, the representations of these knowledge states must facilitate fast appraisals. The model must further address the question of how the constructs of appraisal dimensions and coping strategies can be concretely implemented.

Finally, we must consider what types of representations and processes would support these requirements. In accordance with Newell and Simon's Physical Symbol System Hypothesis (Newell & Simon, 1963), we argue that the representation of the person–environment relation is symbolic. More importantly perhaps, we assume that this representation is not unique to appraisal processes, but supports a wide range of cognitive processes. That is, it not only codifies the information required to compute appraisals, but does so in such a way that appraisals can be made rapidly, and can be integrated with other cognitive processes. Note that symbolic representations are a natural fit for appraisal theories that emphasize the tight relationship between emotion and symbolic reasoning. However, it may be argued that symbolic representations neglect the bodily sources (e.g., visceral or somatic feedback) and consequences of emotions emphasized by many emotion theorists (e.g., Zajonc, 1980). Although we do not address bodily origins and effects of emotions in our current model, we believe that these aspects of emotion can be reconciled with our model by assuming some pathway between symbolic and sub-symbolic processes (see Section 2.3.4).

2.3. EMA (EMotion and Adaptation)

EMA is a computational model that realizes these theoretical assumptions and requirements. Previous publications provide details of the approach (see Gratch & Marsella, 2004a; Gratch & Marsella, 2004b; Marsella & Gratch, 2003 and empirical support for the validity of the model (Gratch & Marsella, 2005). Here we provide more specific details of the representational assumptions (necessary to describe our detailed encoding of the example situation above). The description provided here also updates the details of the model. Therefore, some aspects of the model differ from previously published descriptions. In particular, there are differences in appraisal (e.g., expectedness
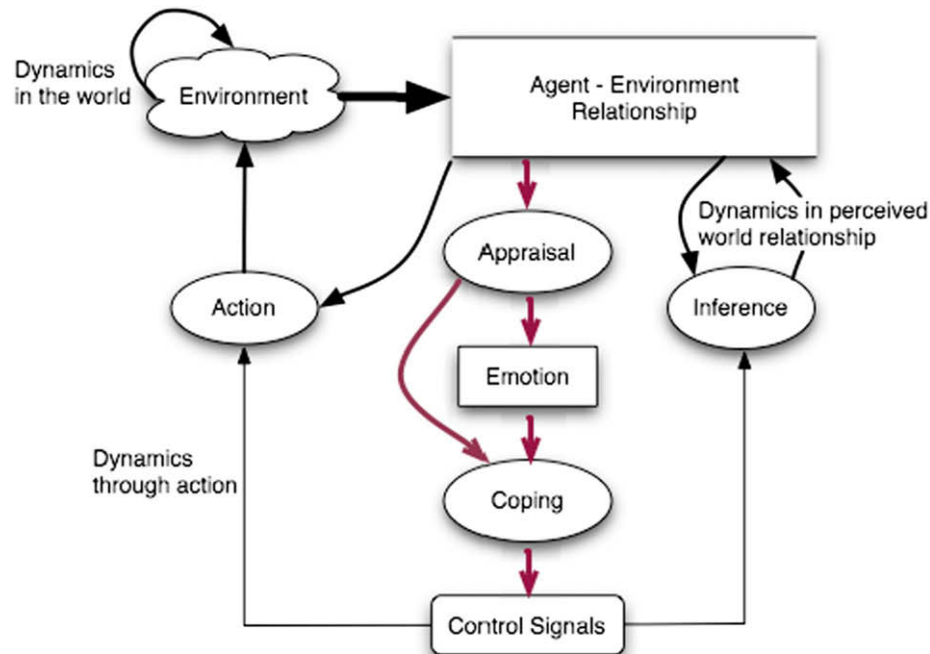
Fig. 2. An illustration of our theoretical assumptions concerning the relationship between appraisal, emotion, coping and cognition, and the sources of dynamics that result.

has been added as an appraisal variable) and coping (e.g., additional strategies and an organization of strategies into an ontology based on the type of representations and processes they impact).

In general terms, we define a computational model of a mental process as a model of a process or processes operating on representations. A computational model of appraisal consists of a set of processes that interpret a representation of the person–environment relationship in terms of a set of posited appraisal variables, and a set of processes (i.e., coping strategies) that manipulate this representation in response to the appraised interpretation. A core requirement for the representation and processes is they support both the rapid and sequential unfolding of emotional responses outlined above.

To address those requirements, EMA uses a representation built on the causal representations developed for decision-theoretic planning, augmented by the explicit representation of intentions and beliefs. Planning representations capture a number of essential distinctions required for computing appraisals, including causal reasoning, the ability to detect future benefits and threats, and the ability to represent the causal agents associated with these benefits and threats. The decision-theoretic notions of probability and utility allow EMA to compute the appraisals of desirability and likelihood. Finally, explicit representations of intentions and beliefs are also critical for distinguishing merely contemplated actions from those an agent is committed to perform, an important distinction for computing attributions of blame and responsibility. Finally, explicit representations of beliefs and intentions are important for

modeling coping strategies, especially emotion-focused coping (e.g., abandoning a commitment to a goal, or wishing-away a belief).

We call the agent's interpretation of its "agent–environment relationship" the (current) *causal interpretation* of the agent. This can be seen as corresponding to the content of the agent's working memory and provides a uniform, explicit representation of the agent's beliefs, desires, intentions, plans and probabilities that in turn allows uniform, fast appraisal processes to operate on this representation, regardless of differences in the phenomena being appraised. In the terminology of Smith and Lazarus, the causal interpretation is a declarative representation of the person–environment relationship as currently construed by the person. Both reactive and deliberative processes map their results into the causal interpretation. Architecturally, this is achieved in EMA by a blackboard-style model (Bower & Cohen, 1982; Corkill, 1991). The causal interpretation encodes the input, intermediate results and output of reasoning processes that mediate between the agent's goals and its physical and social environment (e.g., perception, planning, explanation, and natural language processing). Hence, at any point in time, the causal interpretation represents the agent's current view of the agent–environment relationship, which changes with further observation or inference.

2.3.1. Knowledge representation

In computationally representing the "agent–environment" relationship we draw on a mixture of symbolic and numeric representations common in contemporary
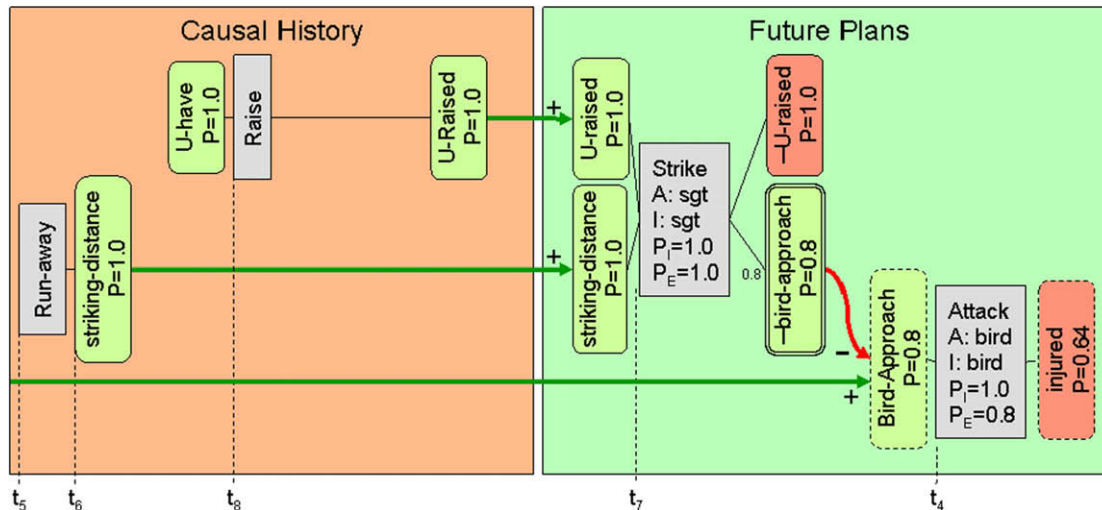
Fig. 3. The causal interpretation, a representation of the agent–environment relationship.

cognitive architectures. Fig. 3 helps illustrate these representations and provides a graphical depiction of a snapshot of the causal interpretation at the point where the actor is prepared to strike the bird with the umbrella. The causal interpretation is organized into a record of past events (the Causal History box in the left of the figure), the *current world state* (implicit in the figure) and possible future outcomes (the Future Plans box in the right of the figure).

States and actions: EMA represents the state of the world as a conjunction of propositions. For example, in Fig. 3 the current state has the actor uninjured, the umbrella raised, and the bird is approaching and in striking distance, indicated by:

–Injured Λ U-have Λ U-raised Λ Bird-approach
　　Λ Striking-distance

Actions are represented with preconditions and effects. For example, striking the approaching bird with the umbrella is represented in Fig. 3 with a Strike action with the precondition that the umbrella is raised and within striking distance, and with the effects that the umbrella will be lowered and the bird is no longer approaching. Actions are assumed to have duration and their effects can occur asynchronously. For example, when executing STRIKE, we may first observe the umbrella to be lowered and subsequently observe the bird to cease its forward progress. At any point in time, several actions may be executing simultaneously and several action effects may be anticipated.

Beliefs and intentions: States and actions are annotated with epistemic variables representing the beliefs, desires and intentions of agents in the situation. In Fig. 3, the agent named "sgt" (short for "sergeant" as the actor in the scenario was playing the role of a military sergeant) intends the Strike action: the terminology "A: sgt" indicates the sergeant is the performer of the action and "I:

sgt" indicates the action is intended.[2] Beliefs correspond to commitments to the truth value of propositions and are binary (true or false) although probabilities (mentioned below) represent a measure of the certainty in this commitment. In Fig. 3, beliefs are indicated by the color/shading of propositions. Light green (or lightly shaded in black and white versions of this document) indicate propositions believed to be true. Red (or darkly shaded) propositions indicate propositions believed to be false.

Causal relations: In addition to states and actions, the causal interpretation represents several relationships between actions and states. Establishment relations (also called "causal links" in the planning literature) represent that an effect of some of some action establishes a precondition of some other action. These are indicated by a direction arrow between states with a "+" sign at the head of the arrow. For example, in Fig. 3, the RAISE action has an effect, U-RAISED that establishes the precondition of the STRIKE actions (the fact that this action is in the causal history indicates that the umbrella has already been raised). Threat relations ("causal threats") represent that the effect of some action blocks (unestablishes) the precondition of another action. These are indicated by an arrow with a minus sign at the head. In Fig. 3, the STRIKE action has the effect that the bird is no longer approaching, which blocks a precondition of ATTACK. Finally, actions can be ordered in time which is indicated graphically by the left-to-right ordering of steps.

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[2] The model allows the agent to distinguish between act intention (agent X intends action A) and outcome-intention (agent X intends effect E to occur). This allows the model to represent unintended effects of action. The model also represents probabilities over these intentions to represent uncertainty in inferring another agent's intentions or uncertainty in another agent's ability or willingness to fulfill public commitments (e.g., agent X asserted to agent Y its intention to perform A, however it has only fulfilled such commitments 50% of the time in the past). To simplify the subsequent discussion we ignore this distinction.

Table 1
Cognitive operators

Cognitive	Update belief	Add/drop a commitment to truth value of a proposition
	Update intention	Add/drop commitment to achieve state/perform action
	Update plan	Add/drop a plan step or resolve-conflicts in a current plan
	Understand speech	Interpret incoming speech act
	Output speech	Produce speech act
	Wait	Default action if no other operator applies (busy wait)
Perceptual	Monitor goal	Orient to observe truth value of goal proposition
	Monitor expected effect	Orient to observe consequence of executing action
	Monitor expected act	Orient to observe initiation of pending action
	Listen to speaker	Orient to speaking agent
	Expect speech	Orient to agent that is expected to speak
	Monitor unexpected event	Orient to event location (e.g., attend to a sound) and record any unexpected change in truth value of propositions
Motor	Initiate-action	Start action (or record start of external observed act)
	Terminate-action	Terminate action (or record end of external observed act)

Probabilities and utilities: States and action have decision-theoretic annotations. *Utilities* represent the preference agents' have for states. For example, we may imagine the actor assigns disutility to being injured but the bird has no preference (zero utility) for the state U-HAVE. In the figure, we only indicate the agents own preferences over states and for simplicity only indicate valence, not intensity (importance): states with double lines have positive utility for the agent and states with dashed lines have negative utility. Probabilities over states represent the agent's certainty in the truth-value of the state at some (partially ordered) point in time. Probabilities over actions are of two forms. P_I represents the likelihood that an agent intends to execute an action; P_E represents the probability that the action can be executed (taking into account the likelihood of precondition satisfaction). In Fig. 3, for example, the STRIKE action can be performed ($P_E = 1.0$) is fully intended by the agent ($P_I = 1.0$), has a 80% chance of stopping the bird but will raise the umbrella with certainty.[3]

2.3.2. Cognitive operators

The field of cognitive science and cognitive modeling has long attempted to model cognitive processes by appealing to computer metaphors. In accordance with Newell and Simon's Physical Symbol System Hypothesis, conventional (non-emotional) cognitive architectures such as ACT-R (Anderson, 1993) and SOAR (Newell, 1990) model human thought in terms of a set of cognitive operators that are proposed in parallel but executed sequentially. The opera-

tors correspond to deliberative processes (typically higher-level processes such as planning or decision-making) that are posited to be relatively slow and sequential (for example, SOAR assumes each operator executes within 50 ms). Reactive processes (such as perceptual updates, memory retrievals, and certain sensory-motor reflexes) are posited to be fast, automatic and parallel. EMA is built on SOAR and adopts these assumptions. EMA organizes mental processes around a set of primitive cognitive operators that utilize and update the current causal interpretation. These operations record perceptual changes, form new inferences, adopt/retract commitments, and initiate/terminate external actions. Table 1 lists the set of cognitive operators that EMA supports.

Some but not all cognitive operators change the contents of the causal interpretation. For example, update-plan may move an action from long-term memory into the Future Plans. However, monitoring actions simply wait 50 ms for some event to occur. In Fig. 3, we indicate time points where the causal interpretation changed with time stamps at the bottom of the Fig. (e.g., t_7). These indicate the discrete time step in which elements are added or deleted from the causal interpretation. For example, in Fig. 3, the ATTACK action was added on at time t_4.

2.3.3. Appraisals

Appraisal theories characterize emotion-eliciting events in terms of a set of specific appraisal variables, but most theories are vague with respect to the processes that underlie these judgments, and even vaguer about how these processes support the dynamic appraisal and re-appraisal. By choosing to implement EMA within the context of a concrete cognitive model, we must make strong commitments concerning the relation between appraisal and other cognitive processes. In particular, we must decide if appraisal is a relatively slow, sequential and deliberate process, a process that is fast and automatic, or some combination of processes.

In contrast to cognitive operators, we assume that appraisal is fast, parallel and automatic. This is achieved

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[3] More generally, probabilities can be seen as a measure of belief and could apply to either past, present or future propositions. For example, I might be uncertain what you ate for breakfast yesterday. EMA currently makes the assumption that the world is fully observable so there is no uncertainty associated with the truth-value of past or present propositions. There is uncertainty about future propositions, due to probabilistic action outcomes (e.g. there is a 50% chance that I will be injured by the bird, if he attacks) and uncertainty about the intentions of other agents (e.g., there is a 50% chance that the bird will attack).

by modeling appraisal as a set of continuously active feature detectors that map features of the causal interpretation into appraisal variables. All significant features in the causal interpretation are appraised separately, simultaneously and automatically. For example, if the causal interpretation encodes an action with two consequences, one good and one bad, each consequence is appraised in parallel and any factors that influence the desirability or likelihood of these consequences are automatically reflected in these appraisals as soon as these factors are recorded in the causal interpretation. In this sense, appraisals do not change the causal interpretation but provide a continuously updated "affective summary" of its contents.

EMA appraises each and every proposition that is represented in the causal interpretation (past, present or future). For example, in Fig. 3, EMA would appraise the undesirable possibility of being injured by the bird, the undesirable fact that the bird is approaching, and the positive possibility that striking the bird will stop its approach. The model associates a data structure, called an *appraisal frame*, with each proposition. The appraisal frame maintains a continuously updated set of appraisal values associated with each proposition. These variables include:

- *Relevance*: A proposition is judged to be relevant if it has non-zero utility for some agent. This includes propositions that have intrinsic worth for the agent (e.g., in Fig. 3, "injured" has negative utility for the "sgt") or other agents in the world for which the agent has explicitly represented preferences (e.g., the "sgt" might represent the belief that the bird assigns disutility to being injured). A proposition may also be relevant if it has no intrinsic worth but may causally impact a state with utility (e.g., raising the umbrella has worth to the extent that it contributes to the success of an action that avoids injury). Other appraisal dimensions are only derived for relevant propositions.
- *Perspective:* The viewpoint from which the proposition is judged. EMA can appraise events from its own perspective but also from the perspective of other agents. For example, if a consequence of some action has positive utility for the actor but negative utility for the bird, this will be appraised as desirable from the actor's perspective but undesirable from the bird's perspective. For the remainder of this article we only consider appraisal from the agent's own perspective (i.e., from the perspective of the actor playing the sergeant).
- *Desirability:* This characterizes the value of the proposition to the agent whose perspective is being taken (e.g., does it causally advance or inhibit a state of utility for the agent). Desirability can be positive or negative. Desirability may be intrinsic, as when a state has immediate value to the agent (e.g., health), or derived, as when achieving the state makes other states with intrinsic value more or less likely (e.g., having an umbrella is a means to the end of protecting oneself from injury).

- *Likelihood:* This is a measure of the likelihood of outcomes. If the state is in the past or present, this will be zero or one indicating if the state is true or false (EMA assumes at present that propositions are fully observable – i.e., there is no uncertainty about the current state of the world). If the state is in the future, this indexes the likelihood that it will occur, derived from the decision-theoretic plan.
- *Expectedness:* This the extent to which the truth value of a state could have been predicted from the causal interpretation. For example, if the agent is executing a "raise the umbrella" action and the umbrella is subsequently observed to be raised, expectedness is high. On the other hand, if some unknown exogenous event changes the truth value of a state predict, expectedness is low (no known action could have predicted the change). EMA in its present version assumes all states as having high expectedness unless they are the consequence of some unknown event.[4]
- *Causal attribution*: who deserves credit/blame. This depends on what agent was responsible for executing the action, but may also involve considerations of intention, foreknowledge and coercion (see Mao & Gratch, 2005).
- *Controllability*: can the outcome be altered by actions under control of the agent whose perspective is taken. This is derived by looking for actions in the causal interpretation that could establish or block some effect, and that are under the control of the agent who's perspective is being judged (i.e., agent X could execute the action).
- *Changeability*: can the outcome be altered by some other causal agent (i.e., is there some other action in the causal interpretation that reverses the truth value of the state in question).

2.3.4. Emotions, mood, and focus of attention

As we noted above, there is considerable controversy concerning the relationship between appraisal and emotion. Authors variously claim that appraisal causes emotion, is a component of emotion (reserving the term emotion for the alignment of appraisal patterns, action tendencies and bodily responses), or even a retrospective cognitive justification for a perceived bodily reaction. Most appraisal theories assume that appraisal causes emotional responses; however, this does not mean that once present,

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[4] There are two senses in which an outcome can be unexpected. The first is when some expectation is previously calculated (I won't win the lottery) and this expectation is disconfirmed (I win!). The second is when no prior explicit expectation existed, as was presumably the case in our example of the bird that flew into the room (see Ortony & Partridge, 1987). This second notion of unexpectedness is the only one that EMA currently recognizes.

Table 2
Mapping from appraisal pattern to emotion label

Appraisal pattern for proposition "p"	Emotion
Expectedness(self, p) = low	Surprise
Desirability(self, p) > 0 & Likelihood(self, p) < 1.0	Hope
Desirability(self, p) > 0 & Likelihood(self, p) = 1.0	Joy
Desirability(self, p) < 0 & Likelihood(self, p) < 1.0	Fear
Desirability(self, p) < 0 & Likelihood(self, p) = 1.0	Sadness
Desirability(self, p) < 0 & Causal attribution(self, p) = other & Controllability(self, p) ≠ low	Anger
Desirability(other) < 0, causal attribution(p) = self	Guilt

an emotion may not, in turn, influence subsequent appraisals. Indeed, considerable empirical research has demonstrated that cognition in general and appraisals in particular can be influenced by irrelevant emotions and moods. For example, listening to sad music can make hills seem steeper or tests more difficult (Clore, Gasper, & Garvin, 2001) and emotions such as anger or sadness can bias the appraisal of other events in emotion-congruent ways (Siemer, 2001). This argues, against a simple unidirectional causal relation between the appraisal of task-relevant features and emotional responses.

In EMA, we support a two-level notion of emotional state – appraisal and mood – that can account for some of the indirect effects of emotion documented in empirical research. The appraisal level determines the agent's coping response but this is biased by an overall mood state. Mood acts as a proxy for certain sub-symbolic (brain or bodily) processes (in the sense of Zajonc, 1980) that we do not yet know how to model but that are important for reconciling appraisal models with empirical observations such as affect-as-information (Clore, Schwarz, & Conway, 1994) and core affect (Barrett, 2006). Our theoretical perspective on mood is that the initial appraisal of a situation leads to the recruitment of brain and bodily resources that facilitate certain mental and physical activities and thereby change the subsequent appraisal of the situation. For example, if an actor's body is in a high state of arousal, it may be easier to cope with physical threats as certain responses are already "energized." However, EMA does not explicitly model such bodily consequences of appraisal.

At the appraisal level, EMA maintains multiple appraisal frames (one for each proposition in the causal interpretation) each of which are labeled with a specific emotion type and intensity, and each competing to determine the agent's coping response. We assign symbolic labels (e.g., hope, joy fear) to appraisal frames, however the label is primarily a convenience (e.g., it facilitates the mapping of appraisal patterns to facial expressions) and it is the specific configuration of appraisal variables determines the agents coping responses. For example, an undesirable and uncontrollable future state (e.g., it looks like a bird is going to strike me on the forehead), would be labeled as fear-eliciting and this appraisal pattern leads to avoidance coping. In some cases, the same frame might generate multiple emotion labels. For example, an unexpected and beneficial outcome would elicit both joy and surprise. Table 2 lists

EMA's current mapping from appraisal patterns to emotion labels.[5]

At the mood-level, individual appraisal frames (and their associated intensities) are also aggregated into a higher-level *mood*. We refer to this aggregate state as the agent's mood because it represents (a) a summary of various appraised events; (b) is disassociated from the original eliciting event (i.e., it is not intentional) and (c) tends to change slowly over time as appraisal frames are added or removed in response to changes in the causal interpretation.[6] The representation of the mood state is currently represented as a set of emotion labels (e.g., Hope, Joy, Fear, etc.) with an [0..1] intensity that is a function of all appraisal frames with the corresponding type. For example, if EMA has several appraisal frames labeled with hope, the intensity of these frames are added and passed through a sigmoid function to map them into the range of zero to one, and serve as the hope component of the mood state. The mood state has an indirect effect on appraisal in that EMA applies a mood adjustment to individual appraisal frames. For example, if an appraisal frame is labeled with hope and has an intensity of X, the mood-adjusted intensity of this frame is X + *Mood* (hope). In this sense mood essentially "bleeds over" into the appraisal process.

EMA's moment-to-moment coping response is determined by a simple activation-based focus of attention model that incorporates both appraisal and mood. Specifically, the appraisal frame that determines coping is the most recently accessed appraisal frame with the highest mood-adjusted intensity.[7] This pattern of appraisal

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[5] Note that Table 2 differs from the original mapping described in Gratch & Marsella, 2004a; Gratch & Marsella, 2004b. The original mapping was based on the work Ortony, Clore and Collins (the OCC model). The change reflects the results of evaluation studies (Gratch & Marsella, 2005) and incorporates controllability into appraisals of anger. This change, in fact, brings the model closer to Lazarus' model (1991). This mapping is not intended to be exhaustive and can be straightforwardly extended to other emotions (though this isn't a central focus of our research).

[6] Note, this bears similarity to how Davis (1981) conceptualizes (nonrelational) happiness.

[7] Specifically, each time a cognitive operator is executed, any appraisal frame associated by any data structure accessed by or changed by the operator is activated. These frames are then "mood-adjusted" and the activated appraisal frame with the highest adjusted intensity is selected and determines the agent's immediate emotional state and coping response.

variables associated with this frame determines the agent's expression and its next coping response. The fact that the appraisal frame is mood-adjusted allows for indirect emotional effects. For example, if and event is appraised as equally hope and fear provoking, the agent will focus on its fears if its mood state contains more fear than hope.

2.3.5. Coping strategies

Another key aspect of EMA is that it includes a computational model of coping integrated with the appraisal process (according to Lazarus's theory). Coping determines, moment-to-moment, how the agent responds to the appraised significance of events. Within EMA, coping strategies are proposed to maintain desirable or overturn undesirable in-focus events (appraisal instances). Coping strategies essentially work in the reverse direction of the appraisal that motivates them, by identifying features of the causal interpretation that produced the appraisal and that should be maintained or altered (e.g., beliefs, desires, intentions and expectations).

In EMA, coping strategies can be seen as control signals that enable or suppress the cognitive processes that operate on the causal interpretation. One way of viewing coping is that cognitive operators mentioned in Section 2.3.2 define a space of atomic actions that could be immediately (reactively) applied to the current representation of the person–environment relationship: These include sensing unknown state features, running away from a threat, refining a plan or adding/dropping goals and intentions. Coping acts as a sequential gate-keeper that sanctions the action congruent with the current appraisal pattern. We organize strategies in terms of their impact on the agent's focus of attention, beliefs, desires or intentions.

2.3.5.1. Attention-related coping.
Certain coping strategies seek to modulate the agent's attention to features of the environment. These coping strategies annotate state propositions (e.g., BIRD-APPROACH), indicating whether or not their truth value should be monitored.

- *Seek information*: Form a positive intention to monitor the pending, unexpected, or uncertain state that produced the appraisal frame. Seek Information is unlike planning/action selection in that actions that fulfill this intention do not achieve a specific goal but rather resolve potential uncertainty concerning the truth-value of certain state propositions. Seek information is preferred if the truth value of the state is uncertain, it changed unexpectedly and if appraised controllability is high.
- *Suppress information*: Form a negative intention to monitor the pending, unexpected or uncertain state that produced the appraisal frame. Suppress information is preferred if the truth value is unambiguous or if appraised controllability is low.

2.3.5.2. Belief-related coping
- *Shift responsibility*: Shift an attribution of blame/credit from (towards) the self and towards (from) some other agent. The agents to whom responsibility is shifted must have some causal relationship to the event (e.g., they facilitated or inhibited the appraised consequence). Shift responsibility is preferred if the consequence has low appraised controllability (see Mao & Gratch, 2006 for more details on causal attributions and re-appraisal, see also; Oh, Gratch, & Woo, 2007).
- *Wishful Thinking*: Increase (lower) the probability of a pending desirable (undesirable) outcome or assume some intervening act or actor will improve desirability. For example, if the appraisal frame is associated with a future action with an undesirable outcome, wishful thinking will lower the perceived probability that this effect will occur. Wishful thinking is preferred if the appraised controllability of the outcome is low.

2.3.5.3. Desire-related coping
- *Distance/Mental disengagement*: Lower utility attributed to a desired but threatened state. For example, if an agent's plan for achieving a goal has a low probability of success, the consequence of distancing is that the agent will come to care less about this goal. Distancing is preferred if the appraised controllability of the appraised outcome is low
- *Positive reinterpretation/silver lining*: Increase utility of a positive side-effect of some action with a negative outcome. For example, if the appraisal frame refers to an undesired outcome of a future action but the action has another outcome that is desirable, this positive outcome will achieve greater importance for the agent. Positive reinterpretation is preferred if the appraised controllability of the appraised outcome is low.

2.3.5.4. Intention-related coping
- *Planning/Action selection*: Form an intention to perform some external action that improves an appraised negative outcome. For example, if a goal is currently unachieved, the agent will form an intention to execute some action that achieves the goal. If the action is not immediately executable, this will trigger a search for possible actions that can satisfy the precondition of this action.[8] This strategy is preferred when the agent has some control over the appraised outcome (i.e., controllability is medium or high).

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[8] Note that this includes actions that directly produce desired consequences as well as actions that indirectly produce desired consequences (e.g., by establishing the preconditions of an action that directly produces a desired consequence). This also includes pre-emptive actions – actions that *confront* the preconditions of another agent's plans, thereby preventing them from producing undesirable consequences – e.g., if I smack the bird it cannot hurt me.

- *Seek instrumental support*: Form an intention to get someone else to perform an external action that changes the agent–environment relationship. For example, if a goal is currently unachieved and the only action that achieves it can be executed by another agent, this will trigger communicative acts (e.g., order or request another party to execute the intended action). This strategy is preferred if the action in question is likely to succeed (i.e., controllability is medium or high).
- *Make amends*: Form an intention to redress a wrong. For example, if the agent performed an action that harms another (i.e., desirability is low for the other and causal attribution is the self), it may seek to make amends (and mitigate the resulting feelings of guilt) by performing an action that reverses the harm. This strategy is preferred if the action in question is likely to succeed (i.e., controllability is medium or high).
- *Procrastination*: Defer an intention to some time in the future. For example, if a goal is currently unsatisfiable, but there is reason to believe that circumstances will change in the future, then wait for an external event to change the current circumstances. This strategy is preferred if the situation is appraised as having moderate or low controllability but high changeability.
- *Resignation*: Drop an intention to achieve a desired state. For example, if a goal is appraised as, essentially unachievable, the agent may abandon this goal. This strategy is preferred if the agent has little appraised control over the state.
- *Avoidance*: Take an action that attempts to remove the agent from a looming threat. Avoidance is unlike planning/action selection in the sense that it is not an action that explicitly addresses the threat (such as an action that re-establishes an unestablished goal, or an action that confronts the preconditions of another threatening action). Rather, it is intended to represent a reflexive reaction to certain situations (e.g., freeze or run away) and domain authors must indicate explicitly that certain actions "avoid" certain threats. Avoidance is preferred if the threat is appraised as uncontrollable.

Not every coping strategy applies to each stressor (e.g., an agent cannot be problem-directed if it is unaware of any actions that may change the situation), but multiple strategies can apply to the same stressor. EMA proposes strategies in parallel but adopts them sequentially. A set of preferences resolves ties. For example, EMA prefers problem-directed strategies if control is appraised as high (take action, plan, seek information), procrastination if changeability is high, and emotion-focus strategies if control and changeability are low.

Note that, in organizing coping strategies in terms of the representational structures they operate upon, we move away from the broad distinction between problem-focused and emotion-focused strategies more commonly used in the coping literature. However, we feel this is a natural outcome of concrete models and that, further, the exercise of making coping strategies concrete highlights fundamental ambiguities in these broad distinctions. For example, plan formation can be seen as problem-focused in that it is directed towards changing the environment but emotion focused in that simply the act of forming an intention can improve one's emotional state even if the intention is never acted upon.

To summarize, an agent's causal interpretation is equated with the output and intermediate results of processes that relate the agent to its physical and social environment. This configuration of beliefs, desires, plans, and intentions represents the agent's current view of the agent–environment relation, which may change with further observation or inference. We treat appraisal as a mapping from domain-independent features of causal interpretation to individual appraisal variables. By allowing observation and inference to maintain the domain-independent features of the causal interpretation on which appraisal is based, their mapping into (values of) appraisal variables can be fast – essentially, it is based on pattern matching. Multiple appraisals are aggregated into an overall emotional state (mood) that influences behavior indirectly, by biasing subsequent appraisals. Coping directs control signals to auxiliary reasoning modules (i.e., planning, action selection, belief updates, etc.) to overturn or maintain features of the causal interpretation that lead to individual appraisals. For example, coping may resign the agent to a threat by abandoning the desire. The causal interpretation could be viewed as a representation of working memory (for those familiar with psychological theories) or as a blackboard (for those familiar with blackboard architectures).

3. Illustration: the bird

Modeling the actor's response to the bird allows us to concretely illustrate how EMA recasts dynamic emotional responses in terms of the underlying dynamics in the world, agent's cognitive processes, and behavioral responses. Purely external processes (e.g., the behavior of the bird) unfold over time, leading to incremental changes in the (perceived) current world state. Purely internal processes (e.g., inferences and mental commitments such as the formation of intentions) unfold incrementally, leading to incremental changes of the internal representation of the agent–environment relationship. Finally, agent-initiated actions (e.g., run away or hit the bird) have a time course and unfold over time. In modeling this example, our goal is not to definitively explain and reconstruct the actual inferences and emotions experienced by this actor – many encodings are possible – however, we describe an encoding that generates the emotional transitions that seems plausible from our video analysis and provides a detailed illustration of these sources of emotional dynamics.

We abstract some details of the model in the following discussion to emphasize issues related to emotional

dynamics. Although EMA is designed to support multi-agent simulations where each agent would have a distinct domain model with (possibly) different states, actions and preferences over states, here we only consider the domain model from the perspective of the human actor. Additionally, we ignore the quantitative aspects of the model: EMA derives the intensity of emotional responses from a decision-theoretic calculus – e.g., the intensity of a threat is a function of the likelihood of the threat times the utility of the goal that is threatened – but these distinctions are secondary for the present example and the reader is referred to (Gratch & Marsella, 2004a; Gratch & Marsella, 2004b) for these details.

To simulate a situation in EMA, we must define a domain model that includes a set of propositions for describing the state of the world, actions that might occur and a set of preferences that agents have over propositions. For the bird domain, we define:

3.1. Propositions and preferences

- SOUND – indicates if there is a sound in the environment. This state is initially false.
- BIRD-APPROACH – indicates that the bird is approaching the agent. Initially this is false.[9] We assume this state has small negative value for the agent.
- U-HAVE – Indicates if the agent has an umbrella (U). This is true in the initial state.
- U-RAISED – Indicates if the umbrella is being held upright (if true) or lowered (if false). This is false in the initial state.
- INJURED – indicates if the agent is injured (if true) or uninjured (if false). We assume a utility distribution that assigns large negative utility to this state if true. In other words, the agent prefers not to be injured. This state is false in the initial state.
- STRIKING-DISTANCE – indicates that the bird is sufficiently far away to successfully hit it with the umbrella. Initially this is false.
- BIRD-INJURED – indicates that the bird is injured. We assume that this state has negative value for the agent. In other words, the agent prefers the bird to be unharmed. This state is initially false.
- ROLEPLAY – Indicates if the agent is participating in the roleplaying exercise. This is initially the agent's only goal and is already true at the start of the simulation.

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[9] Classical planning frameworks, upon which EMA is built, typically require the truth-value of all propositions and their truth value to be specified in advance. It may seem strange to explicitly represent the fact that there is no sound and no approaching bird in the initial state of the world, since there are an infinite number of objects that could be represented. This is an aspect of the frame problem (McCarthy & Hayes, 1969) and there are a number of standard approaches for addressing it and which could be incorporated into EMA. For the purposes of exposition, we have omitted these "extraneous" states in the figures below.

3.2. Actions

- ATTEND-TO-SOUND – this sensing action orients the agent to a sound. Although the action has no explicit effects, we script its operation so that the predicate BIRD-APPROACH is perceived to be true approximately 200 ms after it initiates (based on our video analysis). In authoring this action, we represent that it "senses" SOUND (i.e., this indicates that the action may be selected when coping by seek information on the predicate SOUND).
- ATTACK – this action is performed by the bird and injures the agent and is used to represent the inferred behavior of the bird. It has the precondition that the bird is approaching (BIRD-APPROACH = True). If the action is initiated, the agent will be injured (INJURED = True) with high probability 700 ms later.
- RUN-AWAY – this action moves the agent away from the bird. It has no preconditions. After 300 ms, the action has the side effect that the agent will be far enough away from the bird to "deploy" the umbrella. In authoring this action, we represent that it "avoids" the action ATTACK (i.e., this indicates that the action may be selected by avoidance coping to threats involving the ATTACK action).
- RAISE (the umbrella) – this action raises the umbrella. It has the precondition that the agent has an umbrella (U-HAVE = True) and has the effect that the umbrella will be raised, with high probability, 300 ms after the action is initiated.
- STRIKE (the umbrella) – this action hits the bird with the umbrella. It has the preconditions that the umbrella is raised (U-RAISED = True) and that the bird is sufficiently far away to make a swing successful (STRIKING-DISTANCE = True). It has the effects that the bird will no longer be approaching (BIRD-APPROACH = False) and the umbrella will be lowered (U-RAISED = False). These effects occur 200 ms and 300 ms, respectively, after the action is initiated.
- BIRD-CAUGHT – this action represents the case where the bird becomes caught in the other actor's hair. This action has the effects that the bird is no longer approaching and becomes injured.
- HELP-BIRD – this action can help restore the bird from injury, for example, after being caught in the other actor's hair.

After defining a domain model, the agent is initialized in some initial world configuration and allowed to interact with a simulation environment. Fig. 4 illustrates a snapshot of EMA's causal interpretation three time steps into the simulation. At the start of the simulation, t_0, the agent is uninjured, has a lowered umbrella and has established its single goal of roleplaying. We discuss the evolution of the model at each time step:

Time t_1 (Fig. 4): The scenario begins with an outside event that produces an emotional response (i.e., dynamics
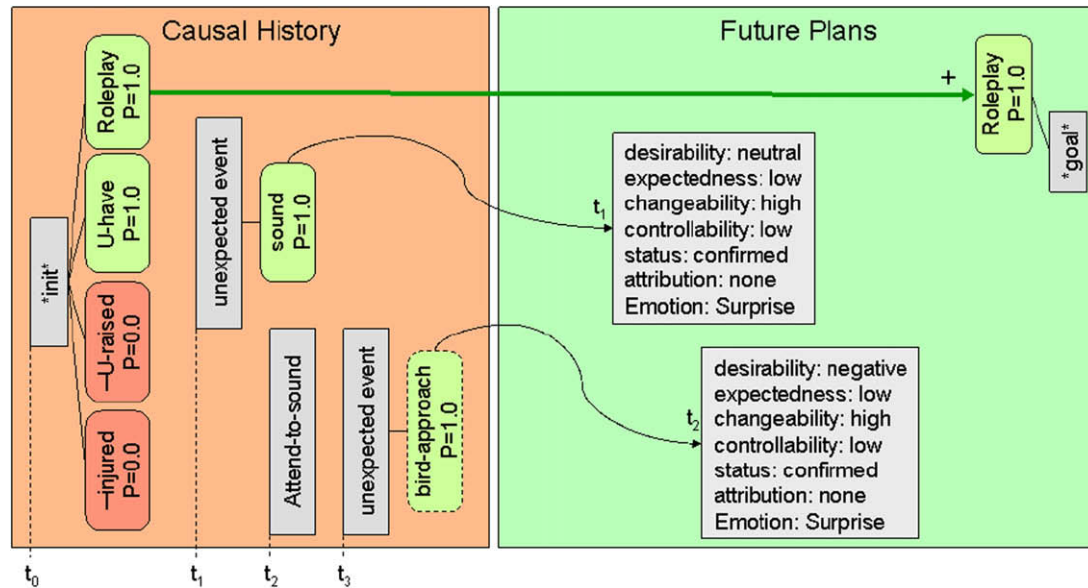
Fig. 4. Causal interpretation at the point the bird is observed.

in the world). The act of the bird striking the window produces makes the proposition SOUND unexpectedly true. This is represented in the causal history as the proposition SOUND becoming true as the result of some unexpected event as no previously known action could have produce such a change. This consequence is automatically appraised as having low expectancy, producing surprise.

Time t_2–t_3 (Fig. 4): This surprise motivates the agent to act, which in turn, produces an additional emotional response (i.e., dynamics through action): the agent copes with the surprising sound by shifting its physical focus of attention and seeking additional information from the environment. Specifically, the agent initiates ATTEND-TO-SOUND at time t_2. Two hundred milliseconds later (t_3), as a consequence of sensing the environment, the bird is perceived to be approaching. Specifically, BIRD-APPROACH unexpectedly becomes true. This is also an unexpected event as there are no known actions that could produce this effect, thus it produces another instance of surprise.

Time t_4–t_5 (Fig. 5): This surprise motivates the agent to reflect on the consequences of this new state of affairs, ultimately leading it to infer that the bird is a potential threat to its health (i.e., dynamics through inference). Specifically, surprise triggers seek-information, which subsequently results in the action ATTACK being added to the causal interpretation.[10] Once the causal interpretation is updated, any consequences of this action are automatically appraised. As the effect INJURED has strong negative value to the agent, this is appraised as undesirable. This update also automatically triggers a shallow assessment of the agent's ability to control this consequence. This assessment

identifies STRIKE as a feasible action (it confronts the preconditions of ATTACK), but one with low likelihood of success as the bird is initially perceived as too close to use the umbrella effectively – i.e., controllability is low. The effect is also seen as uncertain as it occurs in the future. This appraisal pattern results in the appraised emotion of fear.

At t_5, the uncontrollable nature of this undesirable event leads the agent to adopt an avoidance coping strategy, triggering the action Run-away. A side-effect of this action is the agent will be at sufficient distance away from the bird to use the umbrella as a weapon at some point in the future.

Time t_6–t_7 (Fig. 6): Moving away from the bird changes the agent's physical relationship to the bird, affording other response options. Three hundred milliseconds after the agent initiates RUN-AWAY, the effect STRIKING-DISTANCE is observed to be true (t_6). With STRIKING-DISTANCE now true, the ATTACK action becomes more viable as one of its preconditions is now satisfied. This has several consequences. As there is now an action with some reasonable likelihood of confronting the bird's (believed to be) threatening action, the attack is now reappraised as having more control, resulting in anger rather than fear.

This also triggers problem-directed coping (i.e., planning), enabling the cognitive operator, update-plan, to begin to identify actions in the world that address the threat to the agent's health.

At t_7, the agent has begun to construct a plan to address the threat to its health. Specifically, the agent employs a partial-order planning technique called confrontation to block the preconditions of the threatening action. Strike is added to the causal interpretation and its preconditions and effects automatically appraised in parallel. This further illustrates that multiple appraisals may be active at the same time and compete as candidates for coping. As the agent knows of an action that can raise the umbrella

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[10] As our model does not currently implement a cognitive operator that performs intention recognition, we simulate this inference through a domain specific rule that performs the change to the future plans.
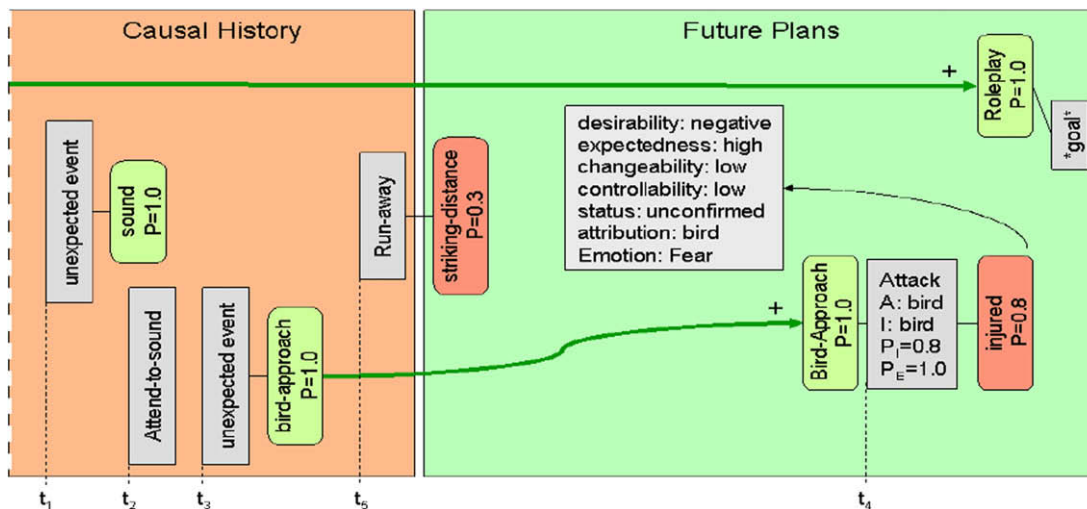
Fig. 5. Causal interpretation as agent begins to run away from the bird.
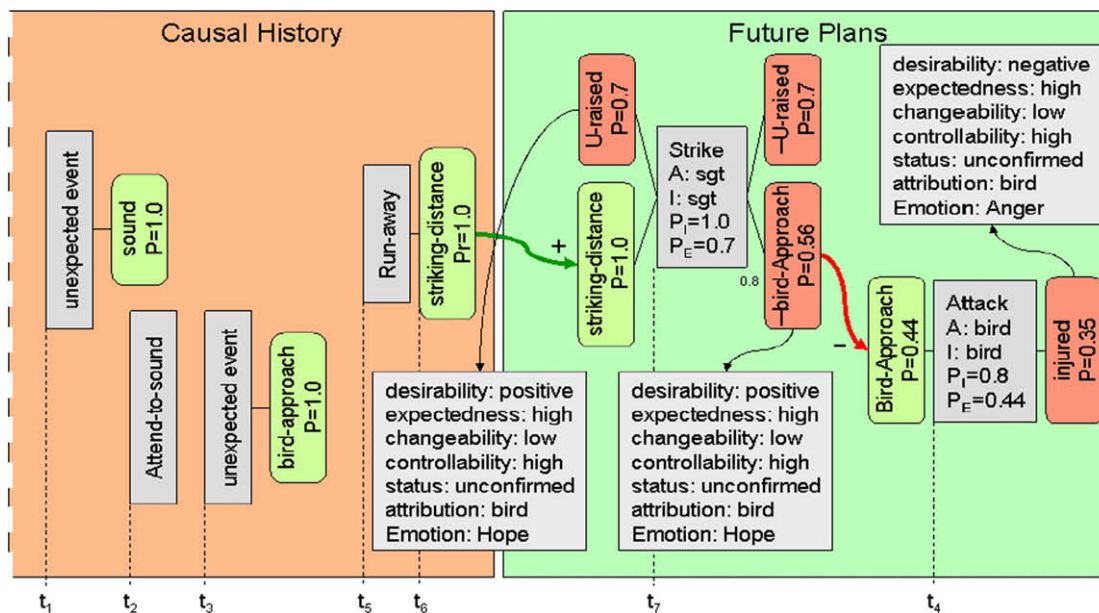

Fig. 6. Causal interpretation as agent has begun to plan how to respond to the bird.

(RAISE), this is appraised as having high control, leading to an instance of hope.

Time t_8–t_9 (Fig. 7): Skipping ahead, Fig. 7 shows the state of the simulation at the point where the bird has become caught in the other actor's hair. At time t_8 the actor has initiated RAISE, the first step in its plan to strike at the bird (the RAISE action was initially added to future plans in response to problem-directed coping and moved to the causal history upon its initiation). Illustrating the dynamic and continuous way EMA models the agent–environment relationship, EMA models the fact that it takes time for the effect of this action to occur. At time t_9 the agent observes that the bird has become caught (BIRD-CAUGHT) and this action is inserted in the causal interpretation with the consequence that the bird is no longer approaching and that it may become injured.

The representation of this event has several consequences. One the one hand, the fact that the bird is no longer approaching (Bird-approach = False) triggers an automatic recalculation of the probability of becoming injured from the bird ($P_E(\text{ATTACK}) = 0.0$), and thus an automatic reappraisal of the threat of injury (which is now appraised as negligible as the probably of the attack is now zero). On the other hand, the fact that the bird is now perceived as injured, which has negative utility for the agent, triggers an automatic appraisal of this effect. This is seen as undesirable and confirmed. It is also appraised as controllable as the agent is aware of an action (HELP-BIRD) that could, without precondition, restore the bird's heath. This, non-intuitively, produces an emotion of Anger (discussed below). This pattern of appraisal variables then leads to the problem-directed strategy of taking
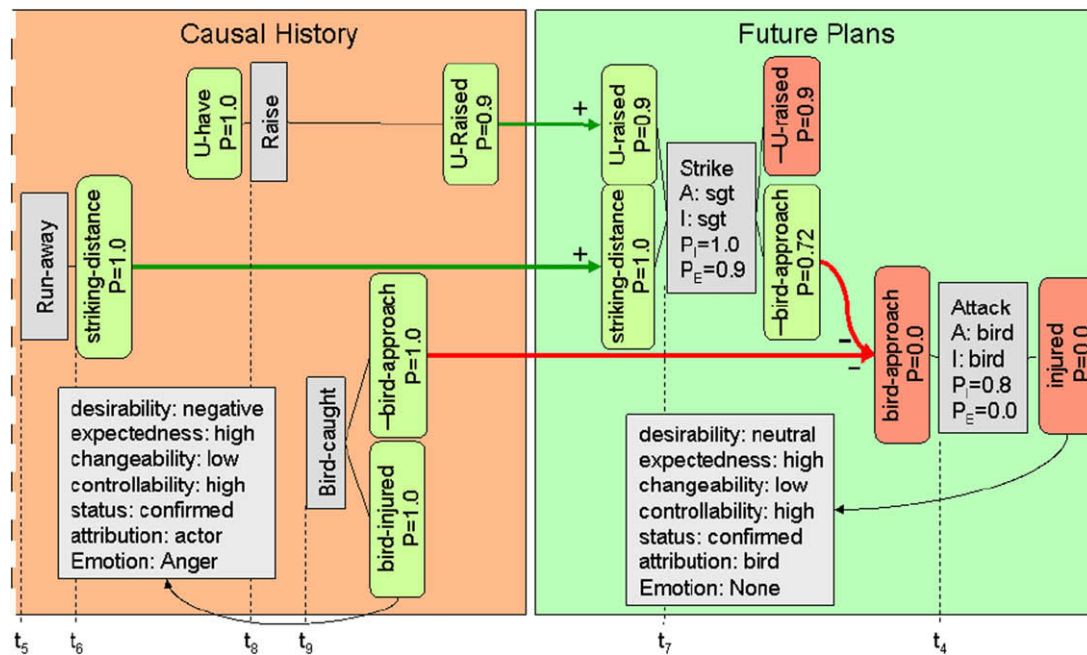
Fig. 7. Causal interpretation at point where bird becomes caught in actor's hair.

4. Discussion

an action, causing the agent to initiate the action of helping the bird and pre-empting the raising of the umbrella.

To summarize, this EMA model of the bird scenario goes through a sequence of transitions caused by dynamics in the agents actual relationship in the world, either by external evolving processes (e.g., actions of the bird) or the agents own actions (e.g., run-away), but also dynamics in the agent's *understanding* of its relationship to the world through the time-course of inferential and perceptual processes. These transitions mirror the changes we postulated for the human actor in the real world scenario described in Section 1.1 and therefore provide one explanation of those changes. Note that, according to this conceptualization, dynamics of these transitions are not due to any intrinsic time course for the appraisals themselves. Nor is it due to sequencing of the component appraisals. Rather the appraisals are pattern-directed, relatively instantaneous, and that time course emerges from the unfolding of physical and cognitive processes.

EMA, consequently, models appraisal as distinct from, but tightly coupled to, the perceptual, cognitive and behavioral processes. In EMA, the generality of appraisal to address complex social interactions as well as physical threats is in large measure due to this separation. Cognition and perception encodes the personal relevance of events in ways that make appraisal simple, fast and general. Fig. 8 illustrates this view of appraisal and coping as tightly coupled to the perception, cognition and behavior processes that inform appraisal and are in turn informed by coping responses. As Fig. 8 makes clear, EMA also generalizes

the role of emotion in the overall architecture of an agent. Coping is often assumed to be a response pattern limited to highly stressful events. However, in EMA, appraisal and coping play a central in mediating response for the agent generally and not just in response to highly stressful events. This is in keeping with the Simon view of emotion as interrupt mechanism.

The exercise of modeling the bird highlights the expressivity and power of EMA but also highlights some limitations. Some of the predicted responses of the actor do not seem to correspond to the actual observed behaviors. For example, at time t_9 the model predicts the actor responds with anger to the injury of the bird but the video analysis suggest something more akin to empathy or "fear for." Some computational appraisal models create different appraisals depending on if the state is a concern for self or other (Elliott, 1992) and EMA exploits this distinction in its definition of guilt, however, the example suggests we extend this capability to more other-directed emotions. Making such a distinction raises some interesting issues. For example, "fear-for" is essentially an empathetic response and one might imagine such appraisals could be blocked if the other entity poses a threat. Incorporating these additional other-directed appraisal, which can be accomplished through the simple addition of some appraisal rules, would enable the alternative coding of the situation where the empathetic response of concern for the bird is triggered, not because the bird is threatened but because it is no longer threatening. This is more consistent with Scherer's treatment of normative checks and our analysis of the video.

Another limitation of EMA is the lack of a detailed model of the time course of physical and mental events.
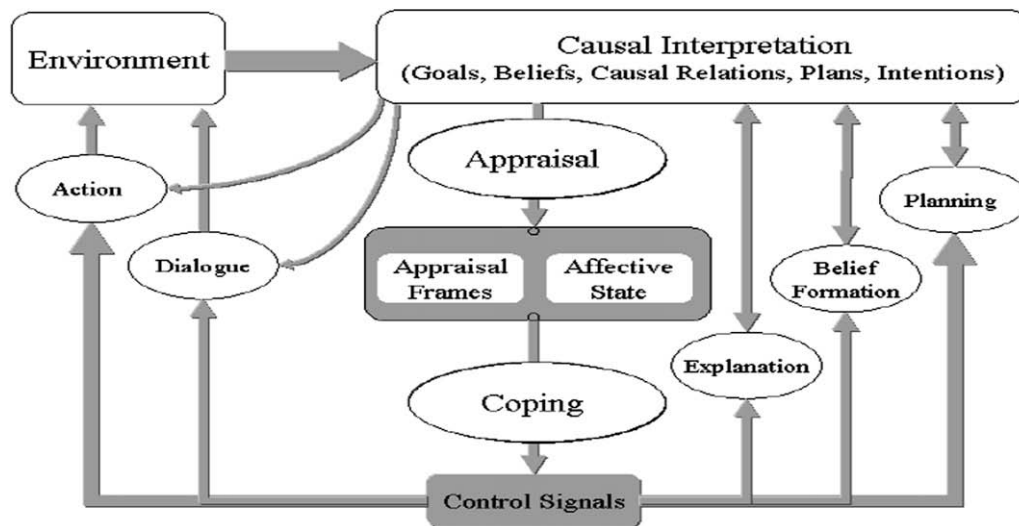
Fig. 8. Our computational instantiation of the cognitive-motivational-emotive system.

When the actor recognizes the approaching bird, this causes a cascade of effects. Cognitive resources are marshaled, triggering a series of inferences about its potential for harm and possible responses. Physiological resources are marshaled, releasing neurotransmitters. Finally, muscles are activated in a sequence, launching the actor's body backwards. Although EMA provides a potential explanation for the initiation of these events, their time course is modeled at a shallow level by indicating in the domain model the number of milliseconds it takes for action–effects to occur. These are free parameters that allow us considerable latitude in fitting our model to data. In this sense, EMA is under constrained and tying these parameters to known reaction-time findings and other cognitive limits would increase the falsifiability and explanatory power of the model.

EMA's use of an explicit domain model is a strength in that it allows us to cleanly separate knowledge from process, but it helps highlight the inherent limitation in experimentally validating appraisal theories. The domain model represents our best guess at the representations and inferences that are going on in the mind of the actor. A challenge in crafting a domain theory is that a modeler is forced to make commitments to how states and actions are represented that may not correspond to the actual mental state of the subject being modeled. One possible way to address such concerns is to adopt more formal domain modeling techniques such as cognitive task analysis (Schraagen, Chipman, & Shalin, 2000) or explore more constrained situations where the "rules of the game" are less open to interpretation.

Modeling a single naturalistic example is illustrative of our theoretical perspective on appraisal and coping, but is not a substitute for rigorous experimental validation of the approach. In prior empirical studies we have shown good consistency between appraisal and coping responses predicted by EMA and human responses in artificial situations (see Gratch & Marsella, 2005; Mao & Gratch, 2006) including emotional dynamics (e.g., subjects were assessed

on vignettes that evolved over time). However, the present situation has many differences in terms of physical engagement and rapid micro-adjustment to the environment that is challenging to reproduce in a laboratory setting. Interestingly, video games and immersive virtual environments present one possible avenue to create dynamic and emotionally-evocative situations and several efforts both inside and outside our laboratory are exploring this option as a means of testing the process assumptions of alternative models of emotion (Kaiser & Wehrle, 1996; Kappas & Pecchinenda, 1999; van Reekum, 2000; Wang & Marsella, 2006). In general, testing our claims about the dynamic nature of emotional processes will require novel experimental paradigms that manipulate the three sources of dynamics that we postulate.

Complementing such empirical studies, the fact that EMA is a computational system allow us to contrast alternative theories based on purely architectural considerations. For example, although EMA, Sequential Checking Theory Scherer (2001) and Smith and Kirby's (2000) two-process theory make similar predictions about the temporal patterning of emotion, they realize this patterning through very different architectures. In not requiring multi-level processes and by achieving patterning without appealing to explicit temporal constraints on appraisal checks, EMA is arguably a simpler and more elegant design. Going forward, a more compelling analysis, however, would try to characterize these differences more formally in terms of such architectural criteria as the computational complexity the underlying algorithm, its generality in terms of the "class" of situations for which the model makes "sound" decisions (according to some rational criteria), etc. Sloman and colleagues have made some attempts to approach emotion from an architectural perspective (Scheutz & Sloman, 2001; Sloman, 2001). More generally, this sort of analysis can be seen as an instance of the problem of rational psychology, which seeks to illuminate psychological processes based on reason alone, rather than on experimentation (Doyle, 2006).

On the more pragmatic side, EMA's architectural commitment to organize certain inferences into a finite set of appraisal dimensions has facilitated the development of large-scale cognitive systems that integrate multiple reasoning capabilities including perception, planning, language processing and nonverbal communication (see Gratch & Marsella, 2007). Appraisal theory suggests a general set of criteria and control strategies that can be uniformly applied to characterize, inform, and coordinate the behavior of heterogeneous cognitive functions. Whether it is processing perceptual input or exploring alternative plans, cognitive processes must make similar determinations: Is the situation/input they are processing desirable and expected. Does the module have the resources to cope with its implications? Such homogenous characterizations are often possible, even if individual components differ markedly. By casting the state of each module in these same general terms, it becomes possible to craft general control strategies that apply across modules and leading to more coherent global behavior. This approach has been applied successfully to the engineering of interactive "virtual humans" that model the perceptual, verbal and cognitive processes of people for a variety of social-skills training systems (Rickel et al., 2002; Swartout et al., 2006; Traum, Swartout, Marsella, & Gratch, 2005).

5. Conclusion

EMA provides a framework for exploring and explaining emotion dynamics and makes specific commitments to how those dynamics are realized. The simulation of the bird example, and the emotional dynamics it reveals, argues that the temporal characteristics of appraisal may be a by-product of other perceptual and cognitive processes that operate on a uniform, common representation scheme of the person-environment relation, the causal interpretation. It supports not only appraisals but also the agent's other cognitive and perceptual processes. By modeling appraisal as a fast, uniform processes operating over the causal interpretation, EMA roots the temporal dynamics in those other processes that operate on the causal interpretation. EMA's description of appraisal is economical, not requiring appeal to alternative fast and slow appraisal processes. Further, coping is also rooted in other cognitive processes, leveraging them to adjust the causal interpretation.

The work on EMA helps to illustrate that computational models of psychological phenomena are potentially powerful research tools. The process of developing a computational model can help concretize theories, forcing commitments about how abstract theoretical constructs are realized. The development of EMA, for example, brought to the forefront the question of how cognition relates to appraisal. In addressing that question, the EMA model makes the argument that a process model of appraisal cannot model appraisal in isolation but rather must take into account the larger system in which it is embedded. Model development can also reveal shortcomings in a theory and identify key conceptual gaps. As an example, EMA's development raised the issue of how the various appraisal checks were realized. This in turn identified that appraisal processes needed to leverage other cognitive and perceptual processes.

A computer model also provides a laboratory that supports experimentation through simulation from which the researcher can derive predictions that can be subsequently tested against human data. Simulation-based experimentation can often be conducted far more efficiently than human experimentation, thereby supporting more systematic and extensive manipulation of experimental conditions. Moreover, it is free of the ethical concerns that are central to any research that involves evoking emotions in human subjects.

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