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Psychological Entropy: A Framework for Understanding Uncertainty-Related Anxiety

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Entropy, a concept derived from thermodynamics and information theory, describes the amount of uncertainty and disorder within a system. Self-organizing systems engage in a continual dialogue with the environment and must adapt themselves to changing circumstances to keep internal entropy at a manageable level. We propose the entropy model of uncertainty (EMU), an integrative theoretical framework that applies the idea of entropy to the human information system to understand uncertainty-related anxiety. Four major tenets of EMU are proposed: (a) Uncertainty poses a critical adaptive challenge for any organism, so individuals are motivated to keep it at a manageable level; (b) uncertainty emerges as a function of the conflict between competing perceptual and behavioral affordances; (c) adopting clear goals and belief structures helps to constrain the experience of uncertainty by reducing the spread of competing affordances; and (d) uncertainty is experienced subjectively as anxiety and is associated with activity in the anterior cingulate cortex and with heightened noradrenaline release. By placing the discussion of uncertainty management, a fundamental biological necessity, within the framework of information theory and self-organizing systems, our model helps to situate key psychological processes within a broader physical, conceptual, and evolutionary context.

Keywords: entropy, uncertainty, anxiety, behavioral inhibition, self-organization

Recent years have witnessed a growing interest in the topic of uncertainty (Heine, Proulx, & Vohs, 2006; Hogg, 2000; McGregor, Zanna, Holmes, & Spencer, 2001; Peterson, 1999; van den Bos, 2001). As the body of research on uncertainty continues to grow, the need for an integrative theoretical framework to establish its psychological significance and provide a context for its neural underpinnings and behavioral consequences has become increasingly apparent. In the current article, we propose that the concept of entropy as derived from information theory provides a useful framework for understanding the nature and psychological impact of uncertainty. By drawing upon dynamical models of self-organizing systems, we argue that uncertainty presents a fundamental (and unavoidable) challenge to the integrity of any complex organism. The entropy-based model developed throughout this article provides an organizing framework for understanding the critical importance of uncertainty management for an individual's survival, well-being, and productivity, situated within a broader evolutionary and physical context. In doing so, it helps to draw together numerous research literatures in which uncertainty plays an important role, integrating them into a coherent theoretical framework for conceptualizing the neural and behavioral responses to uncertain situations.

The article proposes the entropy model of uncertainty (EMU), a framework based on four major tenets: (a) Uncertainty poses a critical adaptive challenge for any organism, so individuals are motivated to keep it at a manageable level; (b) uncertainty emerges as a function of the conflict between competing perceptual and behavioral affordances; (c) adopting clear goals and belief structures helps to constrain the experience of uncertainty by reducing the spread of competing affordances; and (d) uncertainty is experienced subjectively as anxiety[1] and is associated with activity in the anterior cingulate cortex and heightened noradrenaline release.

We begin by describing the origins and definitions of the entropy construct, outlining its relevance for biological organisms in general and human behavior in particular. We then apply this idea to cognitive processes by introducing the construct of *psychological entropy,* defined as the experience of conflicting perceptual and behavioral affordances. We next examine how EMU accounts for our current understanding of the neurophysiology of uncertainty. Finally, we discuss how the cognitive and behavioral consequences of heightened uncertainty can be understood within this entropy-based framework.

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[1] We are using the term *anxiety* in the same manner as Gray and McNaughton (2000), who distinguished it from the emotion of fear. This distinction is further elaborated upon later.

Entropy

Rudolf Clausius (1865), working in the field of thermodynamics, originally defined entropy as the amount of energy within a system that cannot be used to perform work (i.e., cannot be used to transform the system from one state to another). Maximum entropy occurs during complete thermodynamic equilibrium, when energy is equally dispersed across all parts of a system. At this point, no useful work can be performed as work always depends on the movement of energy from one area to another.

Ludwig Boltzmann (1877), a defining figure in statistical mechanics, extended this work by defining entropy as a function of the number of microstates that could potentially comprise a particular macrostate, mathematically linking this definition to Clausius's thermodynamic concept. The more microstates that are possible, given any particular macrostate, the higher the entropy of the observed system. In this respect, entropy reflects the amount of uncertainty about a system: The greater the number of plausible microstates, the more uncertainty about which microstate currently defines the system.

Since World War II, the concept of entropy has been generalized to all information systems, not just thermodynamic ones. Claude Shannon (1948), a seminal figure in the field of information theory, defined entropy as the amount of uncertainty associated with a random variable. Shannon demonstrated that the information content of a given signal could be measured as a function of the number of signals that could potentially have been received. The information content of a signal is thus quantified in relation to the amount of uncertainty reduced by receiving the message; this is directly linked to the prior distribution of possible outcomes.

Although these various definitions of entropy are all mathematically related, only this latter conceptualization has the advantage of generalizing to a broad range of information systems (Jaynes, 1957; Pierce, 1980). Building on this work, Norbert Wiener (1961), the founder of cybernetics, defined entropy as the disorganization within cybernetic information systems (goal-directed self-regulating systems). As a system's disorder and uncertainty increase, its ability to perform useful work is hampered by reduced accuracy in specifying the current state, the desired state, and the appropriate response for transforming the former into the latter.

It is the cybernetic view of entropy that plays a prominent role in modern nonlinear dynamical systems approaches. These approaches deal with the emergent properties of complex systems, with an emphasis on tendencies toward self-organization (Nicolis & Prigogine, 1977). Self-organization describes the emergence of a patterned structure of relationships between the constituent elements of a complex system (Ashby, 1947, 1956). High-entropy states, in this context, reflect a lack of internal constraints among the system's interacting parts, such that knowing the state of one component provides minimal information about the others. Because dynamical systems continually change over time, entropy can be related to the predictability of successive states given knowledge of the current state (Shannon & Weaver, 1949).

According to the second law of thermodynamics, the amount of entropy within a closed system can only increase over time. Any mechanical process involves some irreversible energy loss (e.g., inefficiencies resulting in heat loss), and heat will not move from a colder body to a warmer body without additional energy input. Accordingly, a system moves closer to a state of thermodynamic equilibrium as it performs work. Unless more energy is added, the amount of potential work it can produce will inevitably decrease with time. Information systems also lose energy over time as a result of inefficiencies, so they too will eventually dissipate and dissolve unless additional energy is incorporated to sustain structural coherence and minimize internal disorder. We propose that understanding the relationship between entropy and the potential of systems to perform work (i.e., to pursue and achieve goals) can illuminate the significance of uncertainty to biological systems in general and psychological systems more specifically.

Entropy Management as a Fundamental Principle of Organized Systems

Application of the second law of thermodynamics to psychology produces the first major tenet of EMU, that uncertainty poses a critical adaptive challenge, resulting in the motive to reduce uncertainty. This tenet is partly predicated on research examining the emergence and maintenance of order within complex systems. In his groundbreaking book, *What Is Life?*, the physicist Erwin Schrödinger (1944) argued that living systems survive by reducing their internal entropy, while simultaneously (and necessarily) increasing the entropy that exists in their external environment. Although the total amount of entropy in the universe as a whole can only increase (as expressed in the second law of thermodynamics), living organisms can stem the rise of entropy found within their biological systems by consuming energy from the environment, using it to maintain the integrity and order of their own biological systems, and displacing their entropy into the outside world.

In the dynamical systems literature, this entropy-reduction framework has been extended to the view of biological organisms as *dissipative systems* (Prigogine & Stengers, 1997). For an organism to survive, it must effectively dissipate its entropy into the environment. Dissipative systems are open systems operating far from thermodynamic equilibrium, requiring energy intake to sustain a stable structural organization. If the environment changes to produce more entropy for an organism (thereby challenging its structural coherence), that organism must adopt new patterns of self-organization that are capable of accommodating the environmental changes. Self-organization describes the process by which novel dissipative structures emerge in response to higher entropy levels. Dynamical systems theorists therefore propose that stable information systems survive only insofar as they are able to effectively manage their internal entropy. Those that cannot effectively dissipate this entropy are destroyed, in a Darwinian fashion (Kauffman, 1993). One consequence of this process is that complex systems tend to return to a relatively small number of stable, low-entropy states (known as *attractors*; Grassberger & Procaccia, 1983). This is because the vast majority of states that these systems could theoretically inhabit do not provide effective entropy management and are therefore characterized by instability.

Given that the principles of entropy and self-organization can be employed to examine any complex information system, it may not be surprising that these frameworks have also been used to study psychological phenomena (Barton, 1994; Carver & Scheier, 2002; Hollis, Kloos, & Van Orden, 2009; Vallacher, Read, & Nowak, 2002). For instance, researchers have observed self-organizing dynamics during the problem-solving process (Stephen, Boncoddo, Magnuson, & Dixon, 2009; Stephen, Dixon, & Isenhower, 2009). In particular, as an initially adopted strategy becomes ineffective, a quantifiable increase in the entropy of the problem-solving behavior is observed (measured as the irregularity and unpredictability of participants' responses). This increase in behavioral entropy precedes subsequent changes in solution strategy, followed by a return to predictable, stable, low-entropy behavioral patterns. What this suggests is that cognitive-behavioral systems follow the same basic principles as other dissipative systems. If the system finds itself unable to effectively handle environmental challenges, its internal entropy levels will increase and force the adoption or development of alternative cognitive structures. Alternatively, if such structures cannot be found, the system may fail to adapt, become overwhelmed, and start to deteriorate.

Similar interpretive frameworks have been applied to understanding the neural substrates of cognitive operations. In particular, a number of techniques for quantifying entropy levels within neural systems have been developed (Borst & Theunissen, 1999; Nemenman, Bialek, & de Ruyter van Steveninck, 2004; Paninski, 2003; Pereda, Quiroga, & Bhattacharya, 2005; Strong, Koberle, de Ruyter van Steveninck, & Bialek, 1998; Tononi, Sporns, & Edelman, 1994). Several models of neural functioning suggest that patterns of neural activity are also characterized by transitions between familiar low-entropy attractor states, albeit within the context of a great deal of complexity and chaotic activity (Amit, 1992; Tsuda, 2001). Karl Friston and colleagues, for example, have explicitly emphasized the importance of entropy minimization as an organizing principle of neural function (Friston, 2009, 2010; Friston, Kilner, & Harrison, 2006). According to these authors, an important goal of any nervous system is to minimize the experience of entropy and unpredictability by continually modifying neural structures in response to environmental information that arises during goal pursuit. They proposed that the minimization of entropy at the neural level supports cognitive and behavioral adaptation at the level of the individual by providing more pragmatically adaptive representations of the environment. Within a dissipative systems context, the brain is able to adapt to changing environmental events and contingencies by continually reforming its patterns of structural organization, minimizing the entropy that is encountered while trying to satisfy the organism's basic needs (Friston, 2010; Kelso, 1995). The effort to reduce the spread of entropy is an ongoing process, as entropy levels will continually fluctuate as the brain shifts through dynamic patterns of activation and connectivity. It is the psychological experience of entropy that we focus on in our model and to which we now turn.

Psychological Entropy: Uncertainty in Perception and Action

From an evolutionary perspective, the fundamental goal of a nervous system is to integrate appropriate perceptual frames and behavioral responses with the steady flow of sensory information, so that biological needs can be adequately satisfied (Swanson, 2003). Consequently, there are two primary domains of uncertainty that must be contended with from a psychological perspective: uncertainty about perception and uncertainty about action. The second major tenet of EMU, elaborated below, is that uncertainty can be understood psychologically in terms of the conflicting actions and perceptions that can potentially be brought to bear on a given situation.

In any situation, the organism is presented with an array of perceptual and behavioral affordances that specify the possible actions that can be implemented (Gibson, 1979). These affordances reflect the combination of incoming sensory information with the cognitive and behavioral potentialities of the organism (Cisek, 2007; Cisek & Kalaska, 2010; Warren, 2006; Zhang & Patel, 2006). The EMU conceptualizes both the perceptual and behavioral domains as probability distributions. Perception can be understood as the interpretation of sensory input in accordance with expectations, motives, and past experience. Accordingly, there is a probability distribution of potential meanings and perceptual experiences that can be derived from any given array of sensory input. This distribution is influenced by both the structure inherent within the input itself and the structure of the perceptual system doing the interpreting. Similarly, in any moment, there is a probability distribution of possible actions that can be brought to bear on the environment. Importantly, these probability distributions are in part subjectively defined.

We contend that the amount of uncertainty associated with a given perceptual or behavioral experience can be quantified in terms of Claude Shannon's entropy formula, which reflects the negative sum of the log probabilities of each possible outcome (see Figure 1A). This formulation indicates that low-entropy levels are reflected in probability distributions in which some outcomes are much more probable than others (see Figure 1B). High-entropy levels, in turn, are associated with flatter probability distributions, in which no outcome is clearly more likely than the others (see Figure 1C).

According to this framework, uncertainty, or psychological entropy, therefore varies as a result of any experience that alters the shape of these probability distributions. The probability of any given action or perception taking place, represented mathematically as $p(x_i)$, is a function of the weighted neural input for that possibility (relative to other possibilities) during the moment of experience. Computationally, the selection of competing affordances appears to occur through a process of parallel constraint satisfaction and pattern recognition (Bishop, 2006; Rogers & McClelland, 2004; Rumelhart & McClelland, 1986), during which the brain's neural networks attempt to find the most appropriate interpretive frame for a situation, given the current pattern of activations (reflecting perceptual input, motivational frames, embodied motor state, etc.). In a simple connectionist network, the strength of activation for any possible action or perception will depend on its combined inputs from sensory experience and memory representations. The strengths of these inputs are in turn influenced by selective attention processes that prioritize information relevant to the current goal (see Figure 1D).[2]

[2] EMU differs from previous applications of Shannon's formula to cognitive psychology (e.g., Hick, 1952) in that it does not focus exclusively on the distribution of objective stimulus characteristics (e.g., the number of response buttons). Rather, our model of uncertainty focuses on the weighted distribution of potential actions and perceptions as subjectively experienced by the individual. This distribution is a function of both the objective stimulus characteristics and the individual's current repertoire of perceptual and behavioral habits. Consequently, EMU is not affected by the same limitations affecting some of these classic information-theoretic approaches that focus only on the distribution of external stimulus characteristics (Luce, 2003).

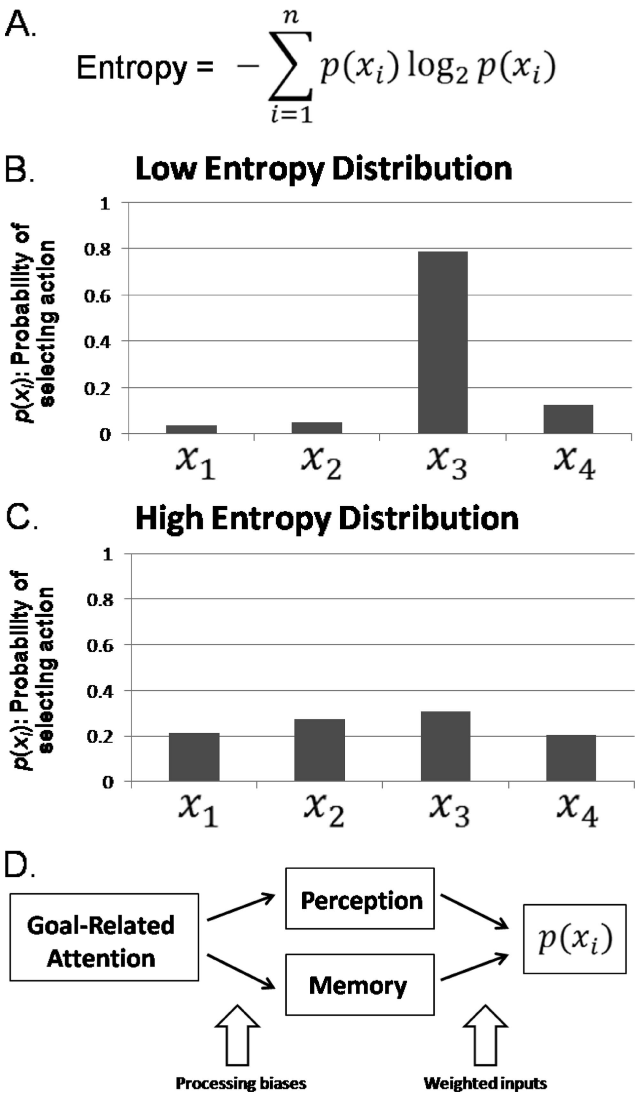

Figure 1. A: Shannon's formula for information entropy. Entropy increases as the number of possible outcomes increases and the probability of any particular outcome, $p(x_i)$, decreases. B: Low psychological entropy occurs during situations in which there is a high probability of employing a particular action or perceptual frame, x_i. C: High psychological entropy occurs during situations in which there are multiple competing frames and behavioral options (e.g., x_1, x_2, x_3), none of which is clearly more strongly activated than the others. D: The probability of any given action or perceptual frame being employed, $p(x_i)$, is a function of the weighted neural input for its deployment, as influenced by the combination of sensory input, strength of memory representations, and goal-related attentional processes.

If the environment is well specified (i.e., personally familiar), the brain is able to settle relatively quickly into a particular perceptual-behavioral frame, based on patterns of habitual responding and reliable estimates of likely outcomes. The brain's operation during these familiar situations is relatively efficient, as there is a rapid matching of environmental input with habitual perceptual and behavioral patterns (reflecting a deep attractor basin in the neural network). The EMU framework describes these situations as states of low entropy because the distributions of possible meanings and actions are heavily weighted toward a single dominant affordance. Progress toward long-term goals can be reached in such circumstances via a simple process of means–ends analysis, using already instantiated procedures, perceptions, and suppositions.

The EMU framework proposes that low-entropy distributions such as those that obtain for familiar situations are characterized by strong neural inputs for a single affordance. This results in a greater degree of computational constraint when interpreting the situation and selecting the appropriate response (i.e., there is a lack of neural competition for alternative outputs). High-entropy distributions, in contrast, have reduced constraint due to a lack of clearly dominant inputs to the perceptual and behavioral systems. These distributions are, accordingly, characterized by higher levels of neural competition and ambiguity (as obtains more often in unfamiliar or unexpected situations). EMU proposes that the amount of uncertainty that an individual will experience in any given situation emerges as a function of the degree of constraint that is placed upon the interpretation of sensory information and the selection of behavioral responses. As indicated by Shannon's formula, the amount of uncertainty (expressed as entropy) will increase in proportion to the number of competing possibilities that must be selected from. Unconstrained situations with a large range of perceived possibilities will result in states of relatively greater uncertainty, while constrained situations with a narrow range of possibilities will result in states of relatively less uncertainty. The first major tenet of the EMU framework indicates that because individuals will be motivated to reduce the experience of uncertainty to a manageable level, psychological discomfort will increase along with the degree of perceptual and behavioral ambiguity within a situation.

While some of the constraint on action and perception emerges from the structural and functional limitations of the human body and brain in combination with past experience, the third major tenet of EMU is that additional constraints are provided by the goals that the individual is pursuing. There is growing evidence that the goals adopted by an individual serve to bias both perception and action in line with goal-relevant information and behavioral options (Aarts, 2007; Bargh & Chartrand, 1999; Bargh, Gollwitzer, Lee-Chai, Barndollar, & Trötschel, 2001). A similar notion is emphasized by clinical psychologists who attempt to help their clients move beyond the narrow horizons provided by maladaptive goals that are difficult or impossible to achieve (e.g., Hayes, 2004). From a neural perspective, goal-related biasing of information flow appears to be instantiated by top-down attentional control mechanisms in the dorsolateral prefrontal cortex, which constrain the activation of perceptual and motor programs in the rest of the brain (E. K. Miller, 2000). As an individual's goals change, so does the distribution of possible meanings and actions that can be derived from the same experience. From a self-organizing systems perspective, goals thus operate as the attractors around which human behavior is organized (Carver & Scheier, 2002).

We propose that whenever a goal is selected, the distribution of possible actions and perceptions that are afforded to an individual is weighted toward those behaviors and interpretive frames that can most efficiently result in movement toward the desired state. Computationally, it appears that this process can be described within the framework of optimal control theory, the application of which allows for the calculation of the optimal path to a goal, while minimizing the cost function associated with goal pursuit (Todorov, 2004; Todorov & Jordan, 2002). For instance, an individual who wishes to find a drink of water is more likely to walk to the water cooler in the next room than the water cooler in the next building. Implementation of either plan would satisfy the goal, but the first is much more efficient, in that it conserves valuable metabolic and material resources. In this sense, optimal control processes help to maintain an economy of action and perception, ensuring the efficient pursuit of a goal. Behaviors that appear to provide the optimal (i.e., most efficient) path to a goal in any given moment thus come to be weighted more heavily in the distribution of possible actions. More complicated higher order goals can also be optimized in such a manner by using dynamic programming techniques that operationalize complex goals as a series of subgoals that can in turn be optimized (Bellman, 1952, 1957; Sutton & Barto, 1981).

It should be noted, however, that the activation of potential actions is a function of their perceived values, rather than their objective utilities. Consequently, the weighted distribution of potential actions will not necessarily conform to classic economic models of rational decision making based on expected utility calculations (Schoemaker, 1982). Rather, the distribution will be influenced by the numerous psychological biases that characterize human decision making, such as loss aversion and the overweighting of extreme but unlikely outcomes (Kahneman & Tversky, 1979; Tversky & Kahneman, 1992), as well as other temperamental biases in perception and action. While there are many specific biases and preferences that influence the relative activation of each possible action (i.e., determining the specific choice that will be made), these are not the primary focus of the EMU framework. Rather, EMU pertains mainly to the weighted distribution of these perceptual frames and possible actions and the amount of entropy that characterizes such distributions.

While goals provide an important source of constraint for the cognitive system, EMU does not suggest that all goals provide the same degree of constraint on the moment-to-moment distribution of perceptual and behavioral affordances. Even the same goal can provide varying levels of constraint in response to different events that facilitate or threaten the goal-pursuit process. In particular, a goal can reduce uncertainty only as long as it allows for rapid functional categorization of sensory information as well as calculation of the (subjectively perceived) optimal response to any given situation. Poorly defined or vague goals are therefore less likely to provide effective uncertainty-reducing effects, as they are incapable of sufficiently narrowing the range of potentially relevant affordances.

Additionally, EMU posits that psychological entropy levels rise whenever the number of obstacles to obtaining a currently selected goal increases. Each of these obstacles will contribute additional uncertainty and inefficiency to the situation, making it harder to compute the optimal action and interpretive frame and, consequently, flattening the probability distribution of affordances. The result of these emerging obstacles is that more work will be needed to transform the system's current state (e.g., hungry and wanting to find food) to the desired state (e.g., full and in possession of food).

In terms of optimal control theory, these obstacles increase the cost function associated with a particular behavioral strategy and, therefore, reduce the weighted activation of related affordances. If the obstacles to obtaining a goal become too severe, the integrity of the goal-pursuit process may be threatened, which EMU predicts would reduce the system's ability to maintain effective constraints on perception and behavior. Removal of these constraints results in heightened uncertainty and less efficient goal pursuit. These principles apply equally to simple biological goals (e.g., satiating hunger) and more abstract higher order and long-term goals (e.g., pursuing a career). If an individual wants to become a famous musician, for example, his or her perceptual and behavioral affordances will be weighted toward goal-relevant opportunities and actions. The integrity of that goal (reflecting its coherence and attainability) can be weakened by the emergence of obstacles that increase the work needed to obtain the desired state (e.g., a broken hand), or it can be strengthened by events that reduce the distance of the goal (e.g., befriending a record producer), with concomitant changes in the experience of uncertainty. Events in the world can increase uncertainty by adding obstacles (jeopardizing the current plan) or reduce uncertainty by providing a clear path to the goal (increasing the efficiency of the current plan).

More generally, a plan involves the estimation of the optimal action for achieving a goal, taking into consideration (a) a particular starting point, (b) a desired end point, and (c) the steps required to transform the original state into the end goal state (Austin & Vancouver, 1996; G. Miller, Galanter, & Pribram, 1971; Schank & Abelson, 1977). Each time that goal-relevant information is received, the costs and probabilities of attaining the outcome using the current strategy have to be recalculated (with greater or lesser uncertainty being introduced in the process). While the natural tendency of all information systems is to return to a state of dissolution and energy dispersal, behavioral plans help organisms to minimize their overall entropy levels (i.e., strengthening their coherence as a functional entity) by providing clear and specific strategies for acquiring needed resources in the face of uncertainty and determining the appropriate way to interpret and respond to environmental input. Effective plans are thus essential tools for combating the inevitable thermodynamic dissolution that comes with time, as they help to maintain the structural integrity of complex biobehavioral systems.

Entropy and Combinatorial Explosion During Uncertainty

As described above, EMU proposes that the entropy experienced by a goal-directed system is inversely related to the amount of perceptual and behavioral constraint provided by a goal. The extent to which a goal is able to effectively provide such constraints is also related to the work needed to attain the goal or, alternatively, the probability of obtaining the goal based on available actions. The work that is required during goal pursuit can be considered in terms of the path length to goal attainment. In some cases, the path length is relatively short, requiring minimal effort, few steps, or transformations of state to achieve the goal and typifying an efficient low-entropy situation of high stability. In other cases, the path length to a goal is relatively long. This is more likely with complex goals that subsume numerous subgoals. While such goals certainly take a longer time to achieve, the system that holds them will remain in a state of relatively low entropy as long as the behavioral path is well specified and the necessary resources are available. Note that it is not the number of subgoals per se that influences entropy levels but rather their specificity and perceived attainability given current knowledge and resources (cf. Maddux, Norton, & Stoltenberg, 1986).

A very different process occurs during situations of uncertainty, however. Uncertainty arises when plans are unexpectedly disrupted (e.g., by the emergence of unforeseen obstacles) and the appropriate perceptual frame and behavioral response are not made immediately clear. When no alternative paths to achieving a desired goal are apparent, there is a massive increase in entropy as the individual's well-delineated plan of action gives way to uncertainty about the best way to construe the situation and move toward the goal (and indeed, whether it is even possible to do so; Bandura, 1982, 1988). In some cases, the disruption of a plan will be caused by a well-understood event (e.g., a flat tire), in which case only behavioral uncertainty will result (i.e., "What should I do?"). In other cases, the nature of the disrupting event itself will not be immediately clear (e.g., an unexpected earthquake), resulting in both behavioral and perceptual uncertainty (i.e., "What is happening, and what should I do?"). While a plan can reduce uncertainty by specifying a dominant behavioral response and interpretive frame, its disruption results in the emergence of a high-entropy distribution of environmental affordances.

To understand how an individual's experience of the world can change so dramatically during states of uncertainty, it is important to remember that the environment is not experienced directly. Subjective experience is based on partial, incomplete, and pragmatically driven representations of the environment. As a result, the experience of the environment (including its meaning and perceptual contours) can change suddenly and quite considerably when perceptual assumptions or behavioral habits are challenged by completely unexpected events that undermine goal pursuit. Under such situations, the appropriate response is no longer clear, and the value and nature of encountered objects become uncertain, concomitant with the sudden activation of competing perceptual and behavioral affordances that were previously constrained by the no-longer dominant goal.

Not all experiences of uncertainty are equally severe. Uncertainty-inducing events that pose a threat to central life goals produce a much larger psychological response. Personal goal hierarchies provide a useful framework for interpreting the importance of a particular experience from an uncertainty-management perspective (Austin & Vancouver, 1996; Carver & Scheier, 1998; Peterson, 1999). The highest level of a goal hierarchy consists of an end state, with the subordinate levels including the perceptions, actions, and subgoals required to achieve the desired end (Powers, 1973). Lower order, behavioral "doing" goals (e.g., getting a good job) are often enacted in support of higher order, more abstract and conceptual "being" goals (e.g., the sense of being a productive member of society; Carver & Scheier, 1998; Powers, 1973; Vallacher & Wegner, 1985). These higher order self-goals organize an individual's actions and perceptions across a large number of situations and over an extended period of time.

The dissolution of these more abstract self-goals has broader implications than the loss of simple behavioral goals, so the concomitant increase of psychological entropy is greater and more widespread. Disrupting a higher order goal means that many behavioral and perceptual affordances previously constrained by this goal are suddenly allowed to vary freely (see Figure 2A). Accordingly, while challenges to lower order goals may lead to relatively minor experiences of anxiety (instantiated as a slight and temporary flattening of the distribution of possible actions and interpretive frames), challenges to an individual's higher order goals can lead to states of profound behavioral and affective destabilization (instantiated as a rapid flattening of the perceptual and behavioral probability distributions across multiple situations; Figure 2B).

Adopting a goal hierarchy perspective helps to explain why people will sometimes voluntarily enter into uncertain situations. In particular, exposing oneself to a measured degree of uncertainty at one level of the goal hierarchy may actually help to reduce uncertainty at a higher order level. An individual who is facing an identity crisis, for example, experiencing dissatisfaction at work, may leave the familiarity of his or her current job to explore alternative career possibilities. In the short term, this will increase the experience of uncertainty as different career options are explored. To the extent that the exploratory behavior is successful, however, the individual will identify a career path that provides a clearer sense of self, thus reducing uncertainty at a higher level of the goal hierarchy and constraining perceptual and behavioral affordances across a broader range of situations.

In terms of the entropy formula, exploration will initially increase entropy levels as the range of perceived options increases. If any of the newly perceived possibilities is deemed to be more desirable than the previously recognized ones, however, it will emerge as the dominant option, and entropy levels will drop below their previous values. Voluntarily confronting and exploring uncertainty in the short term can thus help to reduce uncertainty in the long term by helping an individual to identify the optimal path to a goal. Such exploration is inherently risky, however, as desir-

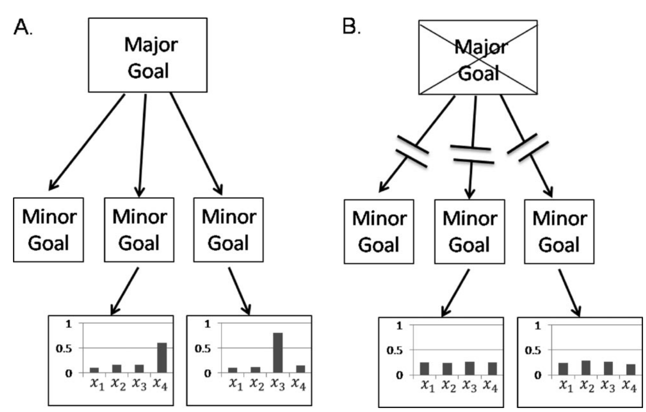

Figure 2. Goals are hierarchically structured such that major goals are achieved through the pursuit of multiple minor goals (or subgoals). Major goals inform a greater number of possible behaviors and situations, with minor goals affecting a smaller subset of situations. In this way, major goals influence a larger part of the experienced world compared to minor goals, serving to constrain various actions and perceptions (each possible representation depicted as x_i) across a broader array of situations (Panel A). Disruption of major goals therefore produces a more widespread increase in psychological entropy (flattening of probability distributions pertaining to more situations and experiences) compared to minor goals (Panel B). Conversely, the disruption of minor goals results in relatively smaller increases in psychological entropy.

able outcomes are seldom guaranteed. Consequently, the risks of voluntary exposure to uncertainty have to be weighed against the potential benefits that might emerge.

Under circumstances of sufficiently severe and potentially traumatic uncertainty, as is likely to emerge when the highest levels of a goal hierarchy are destabilized, the individual can no longer clearly determine the significance of any given object, action, or experience; all of these must be understood and constrained in relation to a particular goal or reference point. Calculating the appropriate response without such a goal becomes extremely difficult, as the number of potential options grows exponentially and the distribution of possible actions and perceptions extends beyond the individual's computational capacities. It should thus be clear that uncertainty is not merely a cognitive phenomenon reflecting a lack of knowledge about a particular domain. Rather, the EMU framework proposes that uncertainty is an intensely affective experience, as it is directly relevant to the ability to fulfill basic motivational needs. Understanding the affective significance of such experiences can be further assisted by examining research on the neurophysiology of uncertainty.

Neurophysiology of Uncertainty

Over the last few decades, substantial progress has been made in describing the neurophysiological processes by which uncertainty is detected and resolved. Such descriptions aid in the elaboration of the fourth major tenet of EMU: that uncertainty is associated with the experience of anxiety and is linked to activation of anxiety-related brain circuits. For an organism to adapt to a complex, ever-changing environment, it is necessary for it to possess flexible cognitive and behavioral frameworks. To maintain such flexibility, the organism must be capable of recognizing discrepancies between its desired or expected outcomes and the outcomes that it actually experiences. Organisms that fail to recognize such discrepancies will continue to use outdated models of the environment and will remain unaware of the dangers and opportunities that lie beyond their current conceptualizations.

Early researchers investigating the neurophysiology of uncertainty identified a process known as the *orienting reflex* or *orienting response.* This reflex serves as an anomaly detector, helping to draw an organism's attention to unexpected sensory events (Pavlov, 1927; Sechenov, 1863/1965; Sokolov, 2002). The behavioral expression of the orienting response involves a rapid shift of attention (usually accompanied by head and eye turn) toward an unexpected or novel stimulus. After repeated presentations of the same stimulus, the orienting response tends to decrease, reflecting the process of habituation.

Neurophysiologically, the orienting response appears to be primarily instantiated in the septo-hippocampal comparator system, which compares neural signals from cortical representations of the environment (models and expectations) with incoming sensory information (Vinogradova, 2001). Whenever there is a mismatch between these two inputs (i.e., whenever the organism's actions or perceptions are not producing the expected or desired outcome), tonic inhibition of the reticular formation by hippocampal CA3 neurons is removed. As a result of this disinhibitory process, emotional arousal is heightened via the release of noradrenaline, and attention is rapidly focused on the anomalous occurrence. As attention is focused on the unexpected event, an updated cortical representation develops, such that future presentations of the same stimulus or event will not produce the same orienting response. If representations of the unexpected event are not updated, then that event will continue to be a source of uncertainty for the organism (along with the associated stress and attentional distraction).

Building on this line of work, Jeffrey Gray published an influential model of anxiety, proposing that mismatch between predicted and actual sensory events is one of the inputs that can produce increased activity within the behavioral inhibition system (BIS; Gray, 1982; Gray & McNaughton, 2000). The BIS is a neural system responsible for suppressing behavior, increasing attention to novel features of the environment, and increasing levels of arousal. Gray identified this system as the neural substrate of anxiety, based on pharmacological studies of antianxiety drugs and their behavioral and neural effects. In particular, Gray associated the BIS with a 7.7-Hz hippocampal theta response, driven by activity in the septal area. This theta response typically accompanies behavioral indicators of anxiety, such as the slowing or cessation of goal-directed behavior. Septal lesions, pharmacological interventions, and other techniques for blocking this theta activity all have the effect of reducing the associated behavioral inhibition.

The septal activity that drives the hippocampal theta response also appears to be dependent upon signals from the dorsal ascending noradrenergic bundle, which originates in the locus coeruleus of the brainstem and which innervates the hippocampus, septum, and some cortical regions (McNaughton & Mason, 1980). Selective lesions of this pathway eliminate the hippocampal theta rhythm, as well as the behavioral expressions of anxiety. The release of noradrenaline in response to faulty expectations thus appears to be one of the key processes in the cascade of neural activity underlying anxiety (Tanaka, Yoshida, Emoto, & Ishii, 2000). It is of interest to note, from the perspective of the EMU framework, that activity in the hippocampal system has also been linked directly to the entropy of a visual stimulus stream; less predictable sequences result in greater hippocampal activity, as anticipated by Gray's model (Strange, Duggins, Penny, Dolan, & Friston, 2005). It is of further interest, from the EMU perspective, that the same neural system and behavioral consequences were observed in response to uncertainty, unexpected nonreward, and cues of impending punishment (Gray, 1982).

In the second edition of Gray's influential book, co-authored by Neil McNaughton, these multiple pathways to BIS activation were integrated within the framework of goal conflict (Gray & McNaughton, 2000), such that BIS activation is most likely when an individual is faced with multiple competing perceptual and behavioral affordances. Accordingly, even approach–approach conflicts, during which an individual is faced with the opportunity to pursue two competing rewards, can trigger BIS-related anxiety. It may seem counterintuitive to think of anxiety as resulting from multiple positive opportunities. However, it is important to keep in mind that EMU predicts greater uncertainty (and hence BIS-related anxiety) whenever the optimal behavioral path is obscured by multiple competing possibilities, regardless of their valence. In these situations, the BIS and its concomitant anxious arousal aid in the search for an appropriate response (cf. Schwartz, 2005).

Gray and McNaughton (2000) also made an important distinction between anxiety and fear, the latter of which is insensitive to anxiolytic drugs (cf. Perkins, Kemp, & Corr, 2007). In particular, they posited that anxiety reflects the experience of BIS-related uncertainty about the appropriate response, while fear reflects the expression of avoidance motivation. Thus, situations characterized by clear threat and a clear strategy for avoiding it are more likely to elicit fear. If, conversely, the situation has a clear threat but does not elicit a clear strategy for threat avoidance (or if there is some incentive to approach the threat), this uncertainty regarding the appropriate behavioral response would produce BIS-related anxiety. This is in addition to the fear and avoidance produced by the threat itself.

The avoidance responses that characterize fear are thought to be instantiated by a neural system distinct from the BIS, the fight–flight–freeze system (FFFS; McNaughton & Corr, 2004). Because fear responses are often situated within ongoing goal pursuit, however, they can increase behavioral uncertainty, which triggers anxiety responses in the BIS. More generally, the appropriate response in a fearful situation is often unclear. In fact, the close relation between these two systems led Gray and McNaughton (2000) to the conclusion that the dispositional sensitivity to threat, as reflected in the personality trait of Neuroticism, was jointly determined by the BIS and the FFFS (cf. Cunningham, Arbuckle, Jahn, Mowrer, & Abduljalil, 2010; DeYoung, Quilty, & Peterson, 2007). Although many emotion researchers regard anxiety as a mild form of fear (e.g., Scherer, 2001), the EMU framework follows Gray and McNaughton's research in conceptualizing anxiety as a distinct affective system associated with goal conflict and uncertainty.

More recently, the anterior cingulate cortex (ACC) has also received attention for its involvement in error processing, conflict monitoring, and uncertainty (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter et al., 1998; Critchley, Mathias, & Dolan, 2001; Holroyd & Coles, 2002; Yeung, Botvinick, & Cohen, 2004). Activity in this brain region is also associated with anxiety and sympathetic arousal (Critchley, Tang, Glaser, Butterworth, & Dolan, 2005; Hajcak, McDonald, & Simons, 2003a, 2003b) and has been conceptualized as a cortical alarm bell that indicates the need for attentional resources to be deployed to address a cognitive or behavioral anomaly. Importantly, this holds true whether the anomaly involves perceptual or motor conflict, performance errors, or uncertainty about a goal-relevant domain.

The functions of the ACC make it appear as a cortical extension of the BIS, as it shares many features with Gray's subcortical network, including electrical activity centered around 7.7 Hz (Luu, Tucker, Derryberry, Reed, & Poulsen, 2003; Pizzagalli, Oakes, & Davidson, 2003), activation following uncertainty and reward prediction errors, associations with increased levels of anxiety, and potentiation by noradrenergic agonists (Riba, Rodriguez-Fornells, Morte, Munte, & Barbanoj, 2005). Additionally, neural activity in the ACC has been directly related to the orienting response in humans, assisting with the detection of novelty and anomaly (Dietl, Dirlich, Vogl, Lechner, & Strian, 1999; Williams et al., 2000). Furthermore, the personality trait of Neuroticism has been linked to ACC activity during the commission of errors, when participants experience response conflict and uncertainty (Haas, Omura, Constable, & Canli, 2007; Hirsh & Inzlicht, 2008; Luu, Collins, & Tucker, 2000; Pailing & Segalowitz, 2004; Paulus, Feinstein, Simmons, & Stein, 2004), as have dispositional measures of BIS sensitivity (Amodio, Master, Yee, & Taylor, 2008; Boksem, Tops, Wester, Meijman, & Lorist, 2006). Accordingly, the fourth major tenet of the EMU framework is that the BIS–ACC system serves as the neural substrate for the experience of uncertainty, which is associated, in part, with the subjective state of anxiety.

Interestingly, uncertainty-related activity in the ACC also appears to occur in response to positive feedback, but only when it is not expected (Jessup, Busemeyer, & Brown, 2010; Oliveira, McDonald, & Goodman, 2007; Pfabigan, Alexopoulos, Bauer, & Sailer, 2011). This finding is consistent with Gray and McNaughton's (2000) proposal that novel and unpredicted events initially result in BIS activation due to the inherent ambiguity of such experiences. Importantly, the EMU framework proposes that it is not the valence of the unexpected event that determines the magnitude of the BIS response to novelty but rather the extent to which it results in the simultaneous activation of competing interpretive frameworks and response tendencies. During unexpected positive events, the interpretation of the event as positive necessarily conflicts with the preexisting belief that no positive event will occur. Although the initial uncertainty about such an event may be resolved relatively quickly, the BIS will be engaged as long as competing representations of the unexpected event are simultaneously active, preventing the adoption of a single dominant interpretive frame or behavioral response.

While the septo-hippocampal system and ACC serve to alert an individual to any anomalous events or conflicting representations that are encountered, a cognitive-behavioral system must also have a means of revising its perceptual and motor programs to develop an appropriate behavioral response to the situation. In this way, future prediction errors and uncertainty can be minimized, and the system's goals can therefore be achieved with fewer unwelcome interruptions. The ACC appears to facilitate this function by subsequently engaging the processing resources of the dorsolateral prefrontal cortex (DLPFC), which can support the selection of the appropriate perceptual state or behavioral response (Cohen, Botvinick, & Carter, 2000; Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000).

While the ACC has been conceptualized as an evaluative system, indicating the need for greater attentional resources, the DLPFC has been conceptualized as an executive system, able to selectively excite or inhibit activity in the rest of the brain to optimize effective goal pursuit (Carter et al., 2000). The DLPFC is involved in planning, conceptual integration, working memory, and cognitive control processes (Kane & Engle, 2002; E. K. Miller, 2000; E. K. Miller & Cohen, 2001), which are of critical value when an organism confronts complex problems that have defied all previously functional conceptual frameworks. The cognitive resources of the DLPFC thus appear to allow for the detailed exploration of an unexpected outcome, so that it can be analyzed for its causes, motivational significance, relevant perceptual properties, and implications for future behavior. Similarly, engagement of the DLPFC should help to reduce uncertainty by facilitating choices between competing interpretive frames (Yoshida & Ishii, 2006). We propose that the extent to which revised cognitive models and behavioral strategies generated during such active engagement are pragmatically adaptive, uncertainty-related activity in the BIS and ACC should decrease. When incoming sensory information is no longer unexpected or in conflict with goal-directed activity, there should no longer be heightened noradrenergic innervation of the septo-hippocampal system.

As described previously, the experience of uncertainty will thus depend upon the clarity and pragmatic effectiveness of an individual's goal (acting as a framework for organizing action and perception) within a given environment. In the next section, we further examine the relationship between uncertainty and goal conflict, at a behavioral level.

Uncertainty and Goal Conflict

The EMU framework proposes that situations of uncertainty will be minimized if an individual has a functionally adequate mental map of the environment and knowledge of the appropriate responses that should be made to further important goals (Peterson, 1999; Peterson & Flanders, 2002). Such an individual has effectively reduced the entropy within the cognitive system, as the distribution of possible meanings and behaviors associated with a given event or situation will be narrowed to a single optimal response. Consequently, less metabolic energy will be wasted during perception and goal pursuit. The well-ordered and adapted knowledge structure of such an individual allows for the efficient execution of the behavioral acts needed to obtain a desired state in the world (i.e., perform work).

Individuals in situations of chronic uncertainty, by contrast, must exert much more energy to accomplish a goal, as they will waste precious metabolic (and cognitive) resources on activities that do not further their interests. The simultaneous activation of conflicting goals can also result in energy loss, as actions that support movement toward one goal may actually hinder progress toward another. For example, a person may wish to attain career success but also spend time with his or her family. In such a situation, the choice to work late to finish a project directly conflicts with arriving home in time for the family dinner.

The highest levels of entropy and metabolic waste will exist when the goal itself is not well specified or in the case when a previously held goal is abandoned and has not yet been replaced by an alternative goal (Carver & Scheier, 2003). In such cases, it becomes impossible to specify the motivational significance of any given event, as there will be no clear reference value by which to judge the experience. No event has a predefined meaning, from an objective perspective. As Hume (1739) so famously implied centuries ago, it is only the subjective relevance of an event to an individual's particular goals (including desires and motivations) that defines and constrains the value of an event, for better or for worse (Baumeister, 1991; Carver & Scheier, 1998; Ferguson & Bargh, 2004; Frankl, 1971; Hirsh, 2010; Little, 1998; Markman & Brendl, 2000; Peterson, 1999). According to the EMU framework, BIS activity should be maximal during situations of complete uncertainty, when there are no clear goal structures constraining the interpretation of an event's significance (or the appropriate behavioral response that should be generated). In such a case, the objects and situations presenting themselves to the observer will suggest an overwhelming jumble of affordances, none of which will be clearly superior to the others in terms of its subjective value or likelihood of producing desired results.

It is important to note the similarity between situations of conflict and uncertainty. At a computational level, conflict reflects the simultaneous activation of competing interpretive frameworks for a given event, with no clear dominance of any one (Berlyne, 1957). If any of the networks supporting these interpretations were clearly more active, based on the constraints of the situation and the individual's knowledge structure, conflict would be minimal and the optimal framework would be rapidly decided (Bishop, 2006; Rogers & McClelland, 2004; Rumelhart & McClelland, 1986). However, to the extent that substantial conflict exists, there are two or more possible frameworks for construing the same situation, with none of them clearly superior to the others. As a result, conflict necessarily implies uncertainty, where the optimal response to a given event remains unspecified. Gray and McNaughton (2000) argued that goal conflict is one of the precipitators of BIS activation, reflecting indecision about how best to construe and respond to a stimulus (e.g., whether to approach or to avoid). Response conflict has also been found to reliably elicit ACC activity and subsequent engagement of the DLPFC (Botvinick et al., 2001; Kerns et al., 2004; Yeung et al., 2004). The resolution of such conflict involves careful examination of the situation to determine the optimal response.

What this suggests is that situations with the fewest constraints can be the most anxiety producing as a consequence of their inherent uncertainty (reflecting the large number of possible interpretive frames and response options). When the affordances of a given situation are equipotential, meaning that no interpretive framework or behavioral response is clearly the most appropriate, there will be a parallel activation of many different perceptual and motor response options. This high-entropy state should engage the BIS and produce the associated experience of anxiety. Note, once again, that this is distinguishable from a situation in which a fear response is produced and a clear escape route is provided; such situations involve a clear dominance of perceptual and behavioral affordances related specifically to escaping the current situation. It is in the situations where the possible responses are truly equipotential (meaning that it is not clear whether or how one should remain, approach, or escape) that a BIS response should be most likely (Gray & McNaughton, 2000). The EMU framework proposes that the levels of anxiety experienced in such situations should be proportional to the degree of uncertainty about the appropriate action. Just as the state of maximal physical entropy occurs when there is a perfect thermodynamic equilibrium of particles within a system, so too does the state of maximal psychological entropy occur when there is a perfect equilibrium of perceptual and behavioral affordances. This occurs when one has absolutely no idea what is happening or what one should do: No candidate options reveal themselves as more appropriate than any other.

High-entropy situations are also distinct from states of behavioral quiescence, where no overt behavior receives strong activation and the individual is in a restful state. Behavioral quiescence is most likely to occur when the potential costs of action are perceived to be higher than the potential rewards, so that refraining from action is perceived as the optimal response (Anderson, 2003). A greater tendency toward inaction is observed, for instance, amongst those who anticipate negative consequences from their actions (Tykocinski & Pittman, 1998) and those with reduced incentive motivation (Depue & Collins, 1999; Hirsh, DeYoung, & Peterson, 2009; Shankman, Klein, Tenke, & Bruder, 2007). States of satiation can likewise foster inactivity by reducing an action's perceived value (Schultz, 2006). During quiescent states, there is a clear perception that no active behavior is required or encouraged by the situation, such that resting or behavioral calmness is the single most clearly afforded option. Amidst uncertainty, by contrast, the relative benefits of action versus inaction can be unclear, resulting in the simultaneous activation of competing perceptual and behavioral affordances for engaging or restraining behavior. These competing affordances in turn prevent the stable adoption of a quiescent state.

Interestingly, the anxiety characterizing highly uncertain situations appears similar to the experience of angst described by existential philosophers, who argued that unconstrained behavioral freedom can lead to a state of despair and insecurity (Fromm, 1969; Kierkegaard, 1844/1957). From the current perspective, such existential angst can be understood as a consequence of heightened BIS–ACC activation when confronting the enormous range of meanings and behavioral possibilities that can be brought to bear on the world. To the extent that the spread of these possibilities is relatively constrained (e.g., by cultural frameworks that specify appropriate responses and perceptual frames), the experience of existential angst should likewise be reduced.

Another important question is whether uncertainty-related anxiety is purely a function of perceptual and behavioral conflict or whether potential threat also plays a critical role. While it is certainly the case that approach–approach conflicts can be anxiety provoking (Schwartz, 2000), this anxiety may in fact be a result of anticipated regret or the perceived consequences of making the wrong choice (Zeelenberg, 1999). There are reasons to believe, however, that uncertainty itself can produce anxiety, even when there is no potential negative outcome. For example, consumer anxiety rises and satisfaction decreases as the number of products to choose from is increased (Iyengar & Lepper, 2000; Schwartz, 2005). Such choice-related anxiety remains even when there are clearly negligible consequences to choosing the wrong product (e.g., the appropriate brand of toothpaste or shampoo). In this case, the anxiety appears to be a function of the indecision itself, rather than the dangers of making the wrong choice. Further evidence that uncertainty itself is anxiety provoking comes from research on self-verification strivings. In particular, people tend to prefer self-congruent feedback, even when that feedback is negative (Swann, Stein-Seroussi, & Giesler, 1992). Depressed individuals, in fact, often prefer to receive negative over positive feedback, as the latter conflicts with their self-concepts and produces a state of personal uncertainty (Swann, Wenzlaff, Krull, & Pelham, 1992; Swann, Wenzlaff, & Tafarodi, 1992). Positive feedback that disrupts one's sense of self is thus an example of nonthreatening information that nonetheless produces uncertainty-related anxiety. The EMU framework helps to make sense of these surprising results by placing them within an uncertainty-management context.

A direct test of the hypothesis that uncertainty itself can be anxiety provoking would involve manipulating representational conflict independently of the evaluative consequences of performance errors. Given that the BIS–ACC system responds to perceptual and motor conflict (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999), we predict that increasing response ambiguity will also increase anxiety, even when no negative consequences are expected. We do, however, expect that situations involving potential threats will magnify the anxiety-provoking effects of uncertainty. At a behavioral level, raising the stakes of a decision should boost affective engagement, as potential gains and losses are both increased, along with the evaluative contrast between the potential outcomes. At a neural level, the amygdalae, which are implicated in vigilance and threat detection (LeDoux, 1996; Whalen, 1998), are densely interconnected with the BIS–ACC system (Margulies et al., 2007; McDonald, 1998). Threat-related information is thus likely to potentiate anxiety-related activity, magnifying the negative effects of uncertainty.

Given that the emergence of uncertainty is often associated with the disruption of ongoing goal pursuit, a key question is whether the resulting anxiety is a consequence of uncertainty itself or the experience of goal frustration. A large literature has linked negative affect to the perceived lack of progress toward a desired goal, and goal frustration can indeed be a powerfully aversive experience (Carver & Scheier, 1998). Gray and McNaughton (2000) similarly identified goal frustration (operationalized as the withholding of an expected reward) as one of the primary inputs into the BIS and thus one of the precursors to the experience of anxiety. Administering anxiolytic drugs, for instance, tends to decrease the behavioral effects of frustration (Gray, 1977; Morales, Torres, Megias, Candido, & Maldonado, 1992). If it is indeed true that goal frustration can itself produce anxiety, EMU suggests that this anxiety will be experienced more intensely in highly uncertain states when the correct response is no longer clear following a frustrating event. If, for instance, progress toward a goal is disrupted by a well-understood obstacle with clear implications, any initial frustration-related BIS activity and anxiety would likely subside relatively quickly (although other negative states related to the behavioral approach system, such as sadness or anger, may nonetheless persist; Carver, 2004; Carver & Harmon-Jones, 2009). Conversely, when the appropriate response remains unclear during states of uncertainty, the added representational conflict would stimulate the BIS over and above the effects of the initial goal frustration. An experimental test of this hypothesis would involve the disruption of goal pursuit with and without the added experience of uncertainty. The EMU framework predicts that even if goal disruption itself may produce anxiety, this anxiety will be amplified in situations where the appropriate response is no longer clear.

Managing Uncertainty: Narratives and Goals

Uncertainty-related anxiety appears to be maximized in situations where there are no clear frameworks for constraining action and perception. Accordingly, the adoption of clear frameworks that resolve the ambiguity that inevitably arises when making sense of the world should reduce the experience of psychological entropy (cf. Heine et al., 2006; McGregor et al., 2001; Peterson, 1999). The EMU framework integrates numerous parallel lines of research that support this possibility, including work on trauma, goal setting, life narratives, and religion.

A traumatic experience is an aversive event powerful enough to undermine the traumatized individual's fundamental assumptions about the world and him or herself (Janoff-Bulman, 1992). These assumptions are relied upon to perceive and act in the world and, once dissolved, must be revised before a person can again move forward. An inability to revise these interpretive structures in the direct aftermath of a traumatic experience provides a partial account for the development of posttraumatic stress disorder (PTSD). PTSD is often seen as resulting from an inability to create an organized narrative account of the trauma (Foa & Riggs, 1993; van Der Kolk & Fisler, 1995), due in part to the disruption of cognitive processes during the encoding of extremely distressing situations (Foa & Kozak, 1986).

Within the EMU framework, traumatic experiences can be understood as events with extremely high degrees of uncertainty, defying clear categorization. Empirically, PTSD is associated with the same physiological systems that underlie the psychological experience of uncertainty (i.e., increased noradrenergic and ACC activity; Bremner, Krystal, Southwick, & Charney, 1996; Hamner, Lorberbaum, & George, 1999; Shin et al., 1997). Traumas that involve greater uncertainty are likewise associated with more severe PTSD symptoms (Goto, Wilson, Kahana, & Slane, 2006), suggesting that chronic uncertainty plays an important role in PTSD. From within the EMU framework, chronic uncertainty (and hence more severe trauma) is likely to result from the disruption of higher order goals and beliefs that previously constrained the spread of perceptual and behavioral affordances across a large number of situations.

To the extent that uncertainty-related anxiety is a key component of PTSD, the EMU framework may also be useful in conceptualizing PTSD treatment in terms of its uncertainty-reducing properties. Therapeutic models of trauma in fact suggest that the generation of a comprehensible narrative account of the traumatic experience is an important part of the recovery process (Foa, Molnar, & Cashman, 1995; Janoff-Bulman, 1992; Tedeschi & Calhoun, 2004). Trauma narration provides a means to develop clearer memory representations of the traumatic experience, control the associated affect, and eventually move beyond the event (Frattaroli, 2006; Harber & Pennebaker, 1992; Herman, 1992; Pennebaker, 1997; Pennebaker, Colder, & Sharp, 1990; Pennebaker, Kiecolt-Glaser, & Glaser, 1988; Pennebaker & Seagal, 1999; Smyth, 1998). Such therapeutic processes can be understood within the EMU framework as helping to constrain the interpretation and behavioral implications of the event within a clear explanatory narrative, thereby dramatically reducing the uncertainty associated with the traumatic experience. Empirical research has supported these ideas, and researchers working in this area employ language that resonates with the EMU framework, focusing on transforming uncertainty into understanding (Pennebaker, 1993; Pennebaker, Mayne, & Francis, 1997).

If the interpretation afforded by EMU is correct, then narrated stories should provide helpful reductions of uncertainty-related anxiety in domains other than those associated with traumatic experiences. The future is a large source of uncertainty as it is necessarily unknown. Consistent with the EMU framework, producing detailed narratives about an ideal future yields psychological and physical health benefits similar to those obtained from narrating a personal trauma (King, 2001). Setting goals for the future, like telling stories, should similarly reduce the uncertainty associated with that future. Research confirms this idea, with the setting of concrete goals acting to reduce anxiety and increase performance (i.e., improving the ability to perform useful work; Locke & Latham, 2002; Morisano, Hirsh, Peterson, Shore, & Pihl, 2010). The integration of past experiences into a coherent, causal representation that includes desires and expectations for the future (constructing a life story; Habermas & Bluck, 2000; McAdams, 2001) has similar benefits (Angus & McLeod, 2004; Baerger & McAdams, 1999). By viewing uncertainty as a fundamental threat to personal stability and integrity, EMU allows one to see how narrating a personal trauma, narrating one's ideal future, setting personal goals, and creating a coherent life story can all have very similar outcomes: All involve reductions in psychological entropy and the associated experience of anxiety.

The EMU model also accounts for how explanatory frameworks reduce uncertainty-related anxiety in another important domain: religion. A recent set of studies compared error-related ACC activity among individuals with high and low levels of religiosity (Inzlicht, McGregor, Hirsh, & Nash, 2009). Highly religious individuals are more likely to have a clear explanatory framework that constrains their interpretation of the world (i.e., an explanatory narrative) and are thus less likely to experience uncertainty in their lives (Hogg, Adelman, & Blagg, 2010). As predicted, the studies found that religious individuals had significantly reduced activity in the ACC in response to personal error, compared to nonreligious individuals. A follow-up study demonstrated that experimentally priming religious ideas similarly reduced ACC activity among believers (Inzlicht & Tullett, 2010).

It has long been argued that one of the functions of religion is to reduce uncertainty about the meaning of the world. However, the EMU predicts that any strong interpretive structure (e.g., political ideology) would constrain the behavioral and perceptual affordances associated with an experience and, therefore, serve a similar uncertainty-reducing function (cf. Amodio, Jost, Master, & Yee, 2007; Hogg, 2005). The uncertainty-reducing function of such belief systems becomes even more pronounced when an individual lives within a community of like-minded others, who are consequently more predictable and less likely to provoke uncertainty (Durkheim, 1912/1995; Kelly, 1955).

It is worth pointing out that while strong beliefs and well-structured social environments will help to reduce uncertainty, they may also result in dogmatic forms of rigidity if taken too far (Fromm, 1969; Jost, Glaser, Kruglanski, & Sulloway, 2003; McGregor, Nash, Mann, & Phills, 2010; Nash, McGregor, & Prentice, 2011). Such dogmatism can easily spread between individual and group levels of interpretation and action (Eidelson & Eidelson, 2003; Peterson & Flanders, 2002; Pincus, Fox, Perez, Turner, & McGeehan, 2008). Attempts to minimize short-term entropy at all costs through the adoption of rigid cognitive structures and behavioral patterns (e.g., by willfully ignoring information that contradicts one's worldview or refusing to explore outside of one's familiar environment) may in fact result in long-term adaptive failure despite the short-term reduction in anxiety. Indeed, excessive rigidity and a reluctance to explore and confront uncertainty have been associated with a variety of pathological outcomes and the failure to adapt to changing circumstances (Bickhard, 1989; Jung & Dell, 1940; O'Connor & Dyce, 2001; Pennebaker, 1989; Peterson, 1999).

Uncertainty and Tonic Noradrenaline

To explore some of the behavioral consequences that can emerge from states of heightened uncertainty, it is worthwhile to examine in more detail the links between uncertainty, noradrenaline release, and heightened BIS activity. The dorsal noradrenergic bundle that Gray linked to uncertainty-related anxiety and activation of the septo-hippocampal system sends broad projections to the rest of the cortex (Glavin, 1985). When released, noradrenaline causes target neurons to react with greater responsivity to their inputs, increasing the activation of cells receiving excitatory inputs and decreasing the activation of cells receiving inhibitory inputs (Servan-Schreiber, Printz, & Cohen, 1990). This modulation of neural activity allows for rapid responding at the expense of reduced behavioral and cognitive flexibility.

Importantly, there appear to be two functionally distinct modes of noradrenaline release, with very different behavioral consequences: a phasic mode and a tonic mode (Aston-Jones & Cohen, 2005). The phasic mode is characterized by short bursts of noradrenaline release in response to goal-relevant information, with a relatively low baseline firing rate when no such information is present. These phasic bursts of noradrenaline are associated with the selective enhancement of neural responsivity following the occurrence of goal-relevant information and are correlated with improved task performance via the facilitated processing of important information (Aston-Jones, Rajkowski, & Cohen, 1999).

By contrast, the tonic mode of operation is characterized by higher baseline firing rates of noradrenergic neurons, such that the release of noradrenaline becomes decoupled from the occurrence of goal-relevant stimuli. This has the effect of producing a broad and nonselective increase in neural responsivity, such that even weak excitatory signals (e.g., those not related to the current task) become enhanced. Consequently, tonic increases in noradrenaline firing rates tend to heighten distractibility and decrease task performance (Aston-Jones & Cohen, 2005).

Interestingly, the alternation between phasic and tonic firing patterns appears to be regulated by inputs from the ACC and orbitofrontal cortex (OFC). As described above, the ACC is involved in uncertainty and response-conflict detection (Botvinick et al., 2001), while the OFC aids in the flexible calculation of reward value (Rolls, 2000; Wallis, 2007). These brain regions appear to signal the noradrenaline system as to whether or not the current goal pursuit is providing suitable rewards (Aston-Jones & Cohen, 2005). As long as the current plan is working effectively and desired rewards are being achieved, the noradrenaline system maintains a low baseline firing rate. When the current behavioral framework is failing to produce the desired results, however, uncertainty and error-related activity in the ACC appear to facilitate a tonic increase in baseline noradrenaline activity.

When baseline firing rates increase during uncertainty, it becomes increasingly difficult to focus on the task at hand, as alternative frameworks and activities start capturing attention (cf. Yu & Dayan, 2005). The EMU framework argues that this increase in tonic noradrenaline release parallels the increase in psychological entropy, as the active goal loses its ability to effectively constrain perception and action. Individuals in this state become more distractible, looking for new sources of reward and stability in their environment (e.g., through the adoption of a new framework or goal). Increased distractibility following uncertainty is consistent with the finding that anxiety facilitates bottom-up attentional capture by salient stimuli while impeding top-down goal-directed control of attention (Eysenck, Derakshan, Santos, & Calvo, 2007).

By adopting this tonic versus phasic perspective on uncertainty, the EMU framework allows for a mechanistic explanation of previously observed behavioral findings. For instance, the perception of real and illusory patterns is enhanced following experimental manipulations that reduce an individual's feelings of control (Whitson & Galinsky, 2008) or challenge his or her conventional interpretive frameworks (Proulx & Heine, 2009). EMU predicts that both of these manipulations lead to a heightened experience of anxiety and concomitant noradrenaline release, as they involve increases in personal uncertainty and psychological entropy. As described above, tonic noradrenaline release produces a nonselective increase in neural responsivity, such that even relatively weak excitatory signals become amplified, thereby increasing their likelihood of producing a response (Aston-Jones, Rajkowski, Kubiak, & Alexinsky, 1994; Usher, Cohen, Servan-Schreiber, Rajkowski, & Aston-Jones, 1999). As a result, individuals with increased tonic noradrenaline activity should be more likely to detect weak or illusory patterns from a noisy channel. EMU thus predicts that the facilitated pattern perception observed in previous research is mediated by BIS–ACC activity and the accompanying increases in tonic noradrenaline release.

The observation that the behavioral effects of uncertainty disappear after participants focus on an important personal value (Proulx & Heine, 2009; Steele, 1988; Whitson & Galinsky, 2008) is also in concord with the EMU framework. These self-affirmations shift attention toward a goal domain that is still acting as a clear and stable source of reward, restoring constraints on perception and action and minimizing the experience of uncertainty. EMU predicts that shifting attention to this other goal domain should help to reduce uncertainty-related BIS activity and accordingly alleviate the noradrenaline-mediated cognitive and perceptual effects of uncertainty. More generally, the EMU framework predicts that attending to a reliable and rewarding goal domain will serve to reduce the experience of psychological entropy and the associated anxiety (cf. Harmon-Jones & Harmon-Jones, 2008; Kay, Whitson, Gaucher, & Galinsky, 2009; McGregor et al., 2010; Tullet et al., in press).

Summary

Entropy refers to the amount of uncertainty within a system, as well as the efficiency with which that system can translate energy into useful work. It is a vitally important concept in the physical and information sciences, and we propose that it has many useful applications within the psychological sciences. Psychological entropy appears inversely related to the integrity of an individual's existence in the world, as reflected in his or her ability to successfully perform work and obtain rewards through goal-directed perception and action. Much of our lives is spent trying to reduce and manage the uncertainty that we encounter. We perform this task by acquiring valuable metabolic and cognitive resources from the environment, while utilizing cultural frameworks that help us to establish a sense of purpose and value. The EMU framework helps to place uncertainty-based models within a broader evolutionary and physical context—one that emphasizes the fundamental importance of uncertainty management in a self-organizing system. Integrating current psychological models with the notion of entropy as derived from cybernetics and information theory allows for greater precision in understanding the nature, dynamics, and consequences of uncertainty-related anxiety.

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