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Adaptation to potential threat: The evolution, neurobiology, and psychopathology of the security motivation system

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ABSTRACT

The risk of improbable, uncertain, but grave potential dangers poses unique adaptive challenges. We argue that to manage such risks, a special motivational system evolved, which we term the security motivation system. Review of work across a range of species indicates that this system is designed to detect subtle indicators of potential threat, to probe the environment for further information about these possible dangers, and to motivate engagement in precautionary behaviors, which also serves to terminate security motivation. We advance a neurobiological-circuit model of the security motivation system, which consists of a cascade of cortico-striato-pallido-thalamo-cortical loops with brainstem-mediated negative feedback. We also detail the broader physiological network involved, including regulation of the parasympathetic nervous system, with emphasis on vagal regulation of cardiac output, and activation of the hypothalamic–pituitary–adrenocortical axis. Finally, we propose that some kinds of psychopathology stem from dysfunction of the security motivation system. In particular, obsessive compulsive disorder may result from the failure of a mechanism by which engagement in precautionary behavior normally terminates activation of the system.

In the natural environment, organisms face the prospect of events that are of low or unknown probability but nonetheless have grave potential consequences, including death. Thus, the management of risk – for example, from predators and disease – is an essential problem for survival. Because such risks, though they may be improbable, have very large consequences for reproductive fitness, it is likely that evolution shaped psychological systems directed toward them.

Rare, high-consequence events have properties that are quite unlike those of relatively more common, less consequential events. For example, because the cost of error is severe (e.g., injury or death), these events present much more limited possibilities for learning through the experience of natural consequences. A modern analogy would be the problem of teaching children not to run out into the street before looking both ways: One cannot simply let them run into the street and learn by finding out for themselves what happens.

Rare, high-consequence events have other special properties as well. Taleb (2007), a risk engineer, has drawn attention to these somewhat counterintuitive properties by calling such events "black swans." Black swans are high-impact outliers—that is, rare and difficult-to-predict events that have great consequences. As suggested by the incorrect generalization that "all swans are white," black swans are inherently unpredictable because they lie outside the realm of usual experience. That is, even close observation of what happens in normal circumstances may provide very little information about what happens rarely, as outliers. For this reason, black swans are very difficult to model cognitively. Indeed, one of Taleb's main themes is that people's attempts to rationally understand rare, high-consequence events typically involve hindsight bias and have virtually no predictive validity. Relying on such illusory patterns is hazardous and does not provide a robust approach for managing risks.

We can readily apply these insights to the evolution of a risk management system. Rare, high-impact events pose special epistemic limitations. Where knowledge is uncertain and the consequence of error is large, what the organism needs is a robust strategy—one that emphasizes precaution in the face of the

Abbreviations: AM, amygdala; BNST, bed nucleus of the stria terminalis; CRH, corticotropin-releasing hormone; GC, glucocorticoids; HPC, hippocampus; LC, locus coeruleus; MOPFC, medial prefrontal cortex and orbital prefrontal cortex; PVN, paraventricular nucleus.

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unexpected. Thus, the underlying mechanisms governing behavior and learning for these types of events may be different than for relatively probable events and ones with relatively smaller consequences.

In view of these special demands, several investigators have proposed the existence of a special motivation system, shaped by evolution for the management of potential threats to fitness. This biologically ancient, "hard-wired" neural system has been labelled somewhat variously—for example, the "defense system" (Trower et al., 1990) and the "hazard-precaution system" (Boyer and Lienard, 2006). In our work, we have called it the "security motivation system" (Szechtman and Woody, 2004). We now turn to characterizing the major properties of this system.

1. The security motivation system

The security motivation system is a reasonably independent module or system in the brain, which evolved in response to the adaptive problems posed by rare, potentially catastrophic risks such as the threat of predation and disease. Evolutionary psychologists, such as Pinker (1997), Tooby and Cosmides (1990, 1992, 2006), and Trower et al. (1990), have proposed that the evolution of such modules contributed to fitness by addressing sets of related, essential problems in adaptation. Such modules are tuned to the detection of particular classes of input, allow the rapid processing of information of potential impact for survival, operate in a relatively automatic and encapsulated manner (separate from other systems), and have a characteristic range of species-typical output behaviors.

Work on such modules suggests three important general properties. First, such a module involves a "suite" of behavioral adaptations, which were selected together and hence tend to become a correlated set of behaviors (Kavaliers and Choleris, 2001; Sih et al., 2004a,b). In other words, the adaptive behaviors are not selected one by one; instead, they are selected as an interrelated set, which consequently has limited plasticity. Second, even though a module may address a range of adaptive problems, it tends to be organized around a core architecture, sometimes called a "bow tie" (Csete and Doyle, 2002). This core architecture supplies a "plug-and-play modularity" (Csete and Doyle, 2002, p. 488) around which a variety of adaptive problems can be organized (Pfaff et al., 2007). Third, such modules tend to function as motivational systems, which drive relevant behavioral responses when activated and temporarily suppress competing motivational systems (Kavaliers and Choleris, 2001).

Because the security motivation system is hypothesized to handle precaution for rare, hard-to-predict threats, rather than responses to relatively common, predictable events, an interesting issue is the conditions that would have been required for such a system to evolve. Along these lines, Wagner (2003) has addressed the question, "How frequent must a risk be and how severe its impact for risk management strategies to evolve?" (p. 47). Rather surprisingly, he showed that catastrophic events so rare that they do not affect most individuals within their lifetime can still be sufficient for the evolution of relevant precautionary behavior. In the case of risk management, he noted that "natural selection does not act continuously on genotypes whose fitnesses differ at all times. Instead, it acts only sporadically through rare catastrophic events" (Wagner, 2003, p. 51). These events include ones that may not normally happen within a particular individual's lifetime (e.g., an epidemic), and thus the behavioral adaptation involved may have a significance that is not evident within such a lifetime. In summary, it is highly plausible that rare, high-impact events provided the selection pressures needed for the evolution of the security motivation system.

1.1. Major characteristics of the security motivation system

Ethological psychologists and ecologists have extensively studied the ways in which animals manage the threat of predation, and this work indicates the major characteristics of the security motivation system. First, animals must engage in sensitive risk assessment, usually on the basis of subtle and indirect cues, to gauge changes in potential danger (Lima and Bednekoff, 1999b). This assessment must occur even in the absence of any tangible evidence of the presence of a predator (Brown et al., 1999), and it involves the evaluation of unpredictable or unclear stimuli of uncertain significance (Blanchard and Blanchard, 1988). To distinguish such indirect cues from the presence of imminent danger, Wingfield et al. (1998) called them "labile perturbation factors." Similarly, Curio (1993) discussed "hidden-risk mechanisms," which are quite diverse and need to be distinguished from predator detection. Signs of potential danger that could affect offspring and members of the animal's social group are also assessed (Curio, 1993). In summary, the security motivation system involves special types of perceptual processing, which are quite unlike those for recognizing imminent danger.

Second, the animal's vigilance and apprehension are readily activated by relatively weak cues (Brown et al., 1999), and this activation dissipates only relatively slowly (Wingfield et al., 1998), even in the absence of further, confirming cues (Curio, 1993; Marks and Nesse, 1994; Masterson and Crawford, 1982). In order to reduce the potentially deadly occurrence of false negative errors (failure to prepare for upcoming danger), it is adaptive for the system to tolerate a high rate of false positive errors (false alarms). Haselton and Nettle (2006) have pointed out that such calibration increases the overall error rate and superficially appears to be "irrational," even though it may be highly adaptive. Nonetheless, the literature on foraging indicates that this calibration represents a delicate trade-off: If animals devote too much time to risk assessment and alleviation, they necessarily suffer a reduction in the time they have for eating and other essential activities (Brown et al., 1999; Brown, 1999; Lima and Bednekoff, 1999a; Sih et al., 2004b). In summary, relatively weak signs of potential danger may readily activate the security motivation system, and once activated, it is slow to deactivate, with a protracted half-life.

Third, the resulting precautionary behaviors involve probing and manipulating the environment to acquire further information about any potential risks (Blanchard and Blanchard, 1988; Curio, 1993). Checking and surveillance behaviors not only gather information, but also have a preemptive, defensive role, in the sense that predators depend on surprise. In summary, the behaviors directed by the security motivation system involve probing and manipulating the environment, both to further the assessment of potential danger and to help alleviate its effects if it occurs.

Fourth, we have characterized security-related behavior as "open-ended," by which we mean that the animal's environment does not typically afford any clear consummatory or terminating stimulus to signal goal attainment (Szechtman and Woody, 2004). As Curio (1993) pointed out, even a predator's disappearance from view does not constitute a clear signal of reduced risk. In the absence of such clear signals from the environment, what terminates security motivation and the related behaviors? We proposed that it is engagement in security-related behavior itself that generates the internal affective signal to terminate security motivation (cf. Glickman and Schiff, 1967). We also proposed that in people this terminator signal is experienced as a feeling of knowing, or subjective conviction. In a somewhat similar vein, Schneier (2008) has noted: "Security is both a feeling and a reality. And they are not the same".

Finally, previous research on other, coexisting behavioral systems that protect animals from noxious events is useful for showing

how the security motivation system is distinct from these other systems. For example, Ohman and Mineka (2001) have proposed that the "fear module" handles fear-based, escape and avoidance learning. It works by conditioning its central motive state of fear to cues of imminent danger, such as the presence of a predator. The security motivation system is readily distinguished from the fear module in three ways: (1) it is based on subtler, unconditioned stimuli suggesting hidden risk, typically in the absence of any signs of manifest danger; and (2) its central motive state is anxiety or wariness, rather than fear, involving activation of distinct brain regions (see Blanchard et al., 2011); and (3) its characteristic behavioral output typically involves probing the environment and gathering information, rather than avoidance. In a somewhat similar vein, Wingfield et al. (1998) emphasized that the organism's response to "labile perturbation factors" – that is, unpredictable environmental changes that may signal the possibility of an upcoming emergency – is distinct from the fight-or-flight response, both in the kinds of behaviors elicited and in its longer time course. Finally, the security motivation system is also distinct from what Trower et al. (1990) called the "safety system," which operates through the positive affect generated by safety cues and positive reward mechanisms (see Hahn-Holbrook et al., 2011).

1.2. Implications of conceptualizing security motivation as a special system

Conceptualizing security motivation as a special system is not just an empty reification; instead, it has some important and testable implications. Most importantly, it implies that there is a hardwired, or dedicated, substrate mediating its operation. Thus, we can analyze the hypothesized system, breaking it into its logical components (or subsystems), and then look for the likely neural bases of these components. This type of modeling is the principal concern of the next part of this article.

The special-system conceptualization also has important implications for developing hypotheses about how security-motivation operations may breakdown and yield pathology. Csete and Doyle (2004) argued that the "bow tie" architecture of such a system, which is based on relatively few core mediating processes, promotes evolvability and robustness; however, the same structure makes such a system vulnerable to "predictable fragilities that can be used to understand disease pathogenesis" (p. 443). Similarly, Flannelly et al. (2007), developing on previous work by Gilbert (1998, 2001) and Nesse (1998), related the development of some types of psychopathology to what they term "evolutionary threat assessment systems" in the brain. Sih et al. (2004a) pointed out that limited plasticity and behavioral intercorrelations, characteristic of a special system (because it evolved as a package), help to explain behavior patterns that appear to be non-optimal or unadaptive in particular contexts. In addition, the special-system conceptualization serves as a framework for relating individual differences to psychopathology. In particular, because behavioral types may reflect alternative strategies for adaptation, individual differences should predict which kinds of situations an individual will manage poorly, leading to vulnerability (Sih et al., 2004b).

Consistent with this general approach to understanding psychopathology, the last part of the present article advances the hypothesis that some psychopathologies, particularly some of the anxiety disorders, can be conceptualized as pathologies of risk assessment and risk management. We argue that what underlies some disorders is a dysfunction in how the activity of the security motivation system is initiated, sustained, or terminated.

2. Neurobiological-circuit model of the security motivation system

Fig. 1 is a flowchart that shows the proposed functional units of the security motivation system and the nature of their interrelations (Szechtman and Woody, 2004). Across the middle of the figure are four major components, with information flowing from left to right. In addition, above and below are three major feedback routes, each with a specified mediator (e.g., Safety Cues).

The first functional component, Appraisal of Potential Danger, evaluates current environmental stimuli, in the context of the individual's learning history and goals, to ascertain the possibility of a potential threat to self or others. If such a potential threat is detected, it sends an excitatory signal to the second component, Security Motivation, which activates an enduring motivational state. This motivational state persists for an extended time even if a change in external stimuli results in the cessation of the signal from Appraisal of Potential Danger. This extended half-life serves to decouple security motivation from short-term changes in external stimuli, which may not be reliable indicators of whether a decrease in potential danger has occurred.

Activation of the Security Motivation subsystem generates two kinds of output that energize and focus the behavior of the individual. First, Anxiety serves as the mediator for feedback to the Appraisal subsystem. This positive feedback signal both provides an interoceptive cue of potential danger and forms part of a loop that tends to sustain the appraisal. Second, the Security Motivation subsystem outputs an excitatory signal to the third major component, Security-Related Programs, which serves as a repository of species-typical programs for the protection of self and others. Activation of this subsystem elicits performance of precautionary acts such as washing or checking that are appropriate given the informational signal from the Appraisal subsystem.

The performance of these acts yields the fourth functional component, Motor and Visceral Output, which in turn generates crucial negative feedback for terminating the activity of the system. One of the routes of this negative feedback has the mediator, Yedasentience. We coined this term to designate an internally generated feeling of goal attainment that is an important byproduct of engagement in precautionary behaviors. It serves as a inhibitory signal for both the Security Motivation and Appraisal subsystems. The diagram shows a second possible route of negative feedback—through the enhancement of Safety Cues, which then have an inhibitory impact on the Appraisal subsystem. This route represents the coacting, perhaps somewhat slower effects of a Safety System, as proposed by Trower et al. (1990), which is otherwise distinct from the Security Motivation System.

Given these proposed functional units and interconnections, what hypotheses might we advance about their corresponding neural underpinnings? Fig. 2 shows our proposed circuit diagram for a neuroanatomical model of the Security Motivation System (Szechtman and Woody, 2004). In part, this proposal adopts the overall structure of neuroanatomical models of motivation (e.g., Brown and Pluck, 2000; Everitt and Wolf, 2002), which are based on functional loops involving cortico-striato-pallido-thalamo-cortical connections, as originally advanced by Alexander et al. (1986) and subsequently elaborated by others (Groenewegen et al., 1999; Haber et al., 1995; Haber et al., 2000; Haber and Fudge, 1997; Haber and McFarland, 1999; Joel and Weiner, 1994; Joel and Weiner, 2000; Penney and Young, 1983). To this type of model of motivation, we have added feedback connections from the brainstem to terminate activity in the loops, as described later in more detail.

In Fig. 2, the proposed cascading neural circuits are color-coded to show their respective correspondence to each of the four functional components in Fig. 1. Accordingly, the circuits are labeled as follows: Appraisal of Potential Danger Loop, Secu-

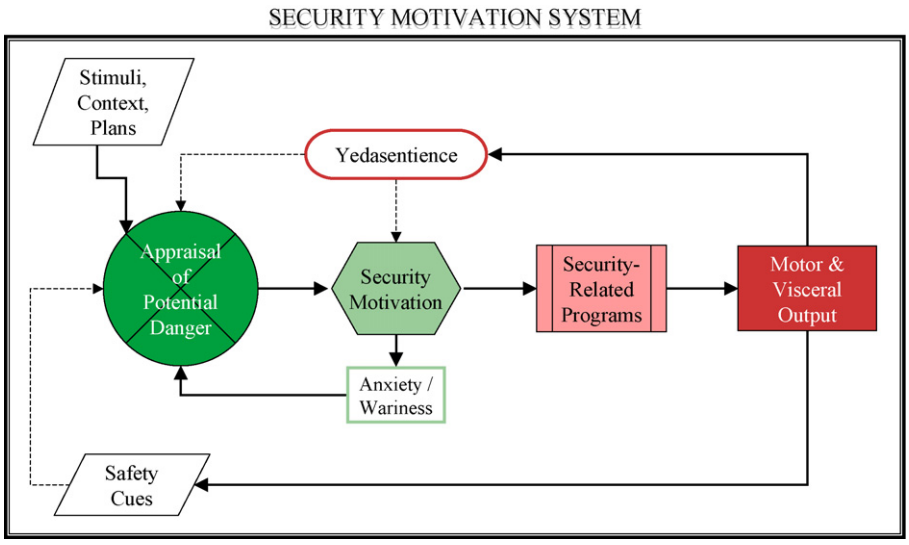

Fig. 1. A conceptual model of the security motivation system and sites of dysfunction producing OCD. Solid arrows indicate excitatory and dashed arrows inhibitory stimulation, respectively. Yedasentience output does not act on environmental input but rather on the Appraisal of Potential Danger and the Security Motivation processors to inhibit their activity. Exposure through motor output to "safety" stimuli provides inhibitory stimulation to Appraisal of Potential Danger.
Modified from Szechtman and Woody (2004).

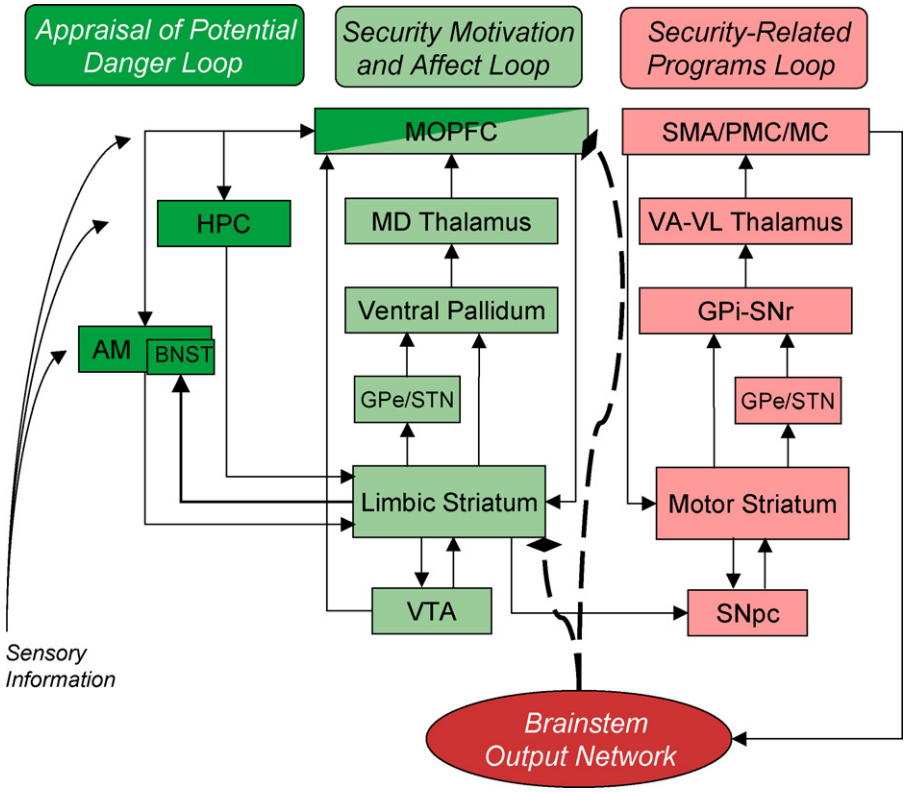

Fig. 2. A neural circuit model of the security motivation system. Each of the 4 distinct subcircuits (loops) subserves one of the functional components in Fig. 1 and identified by corresponding colors. The dashed line indicates possible sites of yedasentience feedback inhibition. *Abbreviations*: AM, amygdala; BNST, bed nucleus of the stria terminalis; GPe, external segment of the globus pallidus; GPi, internal segment of the globus pallidus; HPC, hippocampus; MC, motor cortex; MD Thalamus, mediodorsal thalamic nucleus; MOPFC, medial prefrontal cortex and orbital prefrontal cortex; PMC, premotor cortex; SMA, supplementary motor area; SNpc, substantia nigra pars compacta; SNr, substantia nigra pars reticulata; STN, subthalamic nucleus; VA, ventroanterior thalamic nucleus; VL, ventrolateral thalamic nucleus; VTA, ventral tegmental area.
Reprinted by permission from Szechtman and Woody (2004).

rity Motivation and Affect Loop, Security-Related Programs Loop, and Brainstem Output Network. Let's consider each of these in turn.

2.1. Appraisal of Potential Danger Loop

Because evaluation of potential danger requires the processing of diverse sensory input in the context of ongoing plans, it is likely that the afferents to the Appraisal of Potential Danger Loop come from many areas in the cerebral cortex. Given that processing in this loop crucially involves the emotional processing of stimuli and events, we hypothesize that it consists of interconnected limbic regions known to process motivation-related stimuli. These areas, denoted in Fig. 2 with dark green boxes, include the hippocampus, the amygdala and the bed nucleus of the stria terminalis, and the medial and orbital prefrontal cortex (including the anterior cingulate cortex—see Fiddick, 2011).

These regions are involved in fear-based learning in the face of imminent danger (LeDoux, 2002), but there are strong reasons to believe that they would be involved in the processing of potential danger as well. First, there is likely a continuum across unconditioned, conditioned, and potential threat, such that the corresponding functional circuits are topographically adjacent, consistent with the phenomenon of the spread of allied reflexes (MacDonnell and Flynn, 1966; Szechtman, 1980; Teitelbaum, 1967). As Heimer and colleagues have argued, the different parts in such an anatomically defined continuum "are likely to act on information in a similar fashion, but functional shifts could emerge as a consequence of topographical variations in information that reaches this structure" (Heimer et al., 1997, p. 984). Second, damage to the ventral medial prefrontal cortex or the amygdala causes very impoverished ability to detect potential threat (Bechara et al., 1997, 1998, 1999, 2000).

Finally, our proposal for the Appraisal of Potential Danger Loop includes the neuroanatomical connections needed for it to serve as an integrative gateway for the activation of security motivation. With regard to input, the loop has extensive connections with sensory, associative, and autonomic-affective brain areas (Rolls, 2000; Zald and Kim, 1996). With regard to output, it has extensive connections with the ventral striatum, a key area in the proposed motivation circuit (described next). In particular, there are projections to the ventral striatum from the hippocampus and amygdala, and the medial orbital prefrontal cortex serves as common node between the appraisal and motivation loops, providing an interface between them.

2.2. Security Motivation and Affect Loop

Our proposal for the neuroanatomic circuit of the Security Motivation and Affect Loop, denoted in Fig. 2 with light green boxes, borrows from earlier models of motivation advanced by Everitt and Wolf (2002) and Brown and Pluck (2000). A common set of limbic regions appear to underlie every motivation (MacLean, 1985; Robbins and Everitt, 1996), and the underlying functions of a motive circuit, to sustain goal-relevant action and potentiate perceptual responsiveness, are generic across domains (Kalivas and Nakamura, 1999). Motivational specificity would occur because only a relevant subset of the possible neural circuits would be activated by the output from the Appraisal of Potential Danger Loop. A related aspect of motivational specificity is that the type of affect aroused would be dependent on the conditions that triggered the motivation. For security motivation, we suggest that the associated feeling is one of anxiety or wariness (Masterson and Crawford, 1982). In addition, we suggest that this affective response is mediated by limbic striatum projections to the bed nucleus of the stria terminalis (see the heavy black arrow in Fig. 2), based on evidence indicating its crucial role in anxiety-potentiated startle (Davis et al., 1997; Davis and Shi, 1999; Lang et al., 2000).

As a generalized basal-ganglia-thalamocortical circuit (Alexander et al., 1986), the proposed Security Motivation and Affect Loop is a reverberating feedback loop with the capacity to prolong and sustain activation, a necessary property for motivation, and it connects topographically organized subregions that provide functionally distinct subsets of pathways, selected through the striatal node (Penney and Young, 1983). Reverberation of the subset of pathways related to security motivation would activate a cascade of additional circuits, as described next.

2.3. Security-Related Programs Loop

Our proposal for the neuroanatomical circuit of the Security-Related Program Loop is denoted by the pink boxes in Fig. 2. Work by Berridge and colleagues has shown that the neostriatum serves as specialized region for the organization and implementation of species-typical patterns of behavior (Aldridge and Berridge, 1998; Berridge et al., 1987; Berridge and Whishaw, 1992; Cromwell and Berridge, 1996; see also, MacLean, 1978; Wise and Rapoport, 1989). Accordingly, we hypothesize that security-related programs are implemented in another basal-ganglia-thalamocortical circuit—a motor loop involving the dorsal (or motor) striatum.

There have been several proposals to explain how activity in one basal-ganglia-thalamocortical circuit cascades to another (Groenewegen et al., 1999; Haber et al., 1995; Haber et al., 2000; Haber and Fudge, 1997; Haber and McFarland, 1999; Joel and Weiner, 1994; Joel and Weiner, 2000). Based on this work, the neural progression in our model occurs through one of the series of "spiral" connections (Haber et al., 2000) that connect, in a topographically arranged pattern, midbrain dopamine neurons to the striatum. However, it is also possible that there are other intervening links in the cascade from the "limbic" to the "motor" loop.

2.4. Brainstem Output Network

Finally, the red oval in Fig. 2 represents the crucial role of the Brainstem Output Network in our proposed model. As indicated by the solid arrow from the Security-Related Programs Loop to the Brainstem Output Network, the brainstem nuclei serve as the mediator between the output of the security-related motor programs and behavioral responses. In addition, as depicted by the dashed arrows from the Brainstem Output Network to the limbic striatum and the medial and orbital prefrontal cortex, our model posits that the brainstem plays an essential role in the generation of the negative feedback that inhibits the security motivation and appraisal loops and is experienced as yedasentience.

This hypothesized role of the brainstem is consistent with research strongly implicating it in the production of affect (Panksepp, 1998; Parvizi and Damasio, 2001). However, there is a more specific reason to posit its involvement in a satiety-like mechanism for the security motivation system. Glickman and Schiff (1967) found that even in the absence of reinforcing stimuli, animals engage in investigatory behavior, which consists of motor patterns that are typical of a species but differ widely from one species to another. They proposed that engagement in these species-typical behaviors is, in and of itself, reinforcing. In support of this hypothesis, they used brain stimulation and lesion studies to demonstrate that the same brain system mediated the performance of species-typical behaviors and the reinforcing effects of brain stimulation. Furthermore, they reviewed evidence showing that the circuits for basic components of these species-typical behaviors are fully organized at the level of the brainstem (see also Berridge and Whishaw, 1992). Based on this work, we hypothesize that security-relevant, satiety-like feedback is mediated by

brainstem circuits involved in species-typical motor output for the protection of self or others. By inhibiting security motivation in the limbic system, this brainstem-mediated feedback signal elicits the experience of yedasentience (i.e., the feeling of task completion).

We also propose more specifically that the feedback from the Brainstem Output Network to the security motivation and appraisal loops uses serotonergic pathways. This proposal is consistent with evidence for the role of serotonin as a satiety-like terminator signal (Blundell, 1991; Lorrain et al., 1999). In particular, exhaustion from voluntary exercise – a focused activity that resembles security-related behavior in its lack of external consummatory stimuli – is related to increased brain serotonin, indicating that this neurotransmitter system is involved in terminating motor activity (Bailey et al., 1993; Blomstrand et al., 1989; Dishman, 1997; Heyes et al., 1988). More generally, serotonergic pathways appear to mediate behavioral suppression (Soubrie, 1986) and inhibition of information flow (Spoont, 1992), thus counteracting dopamine systems involved in eliciting active behavior (Antelman and Szechtman, 1975; Kapur and Remington, 1996; Robinson and Berridge, 1997; Wise and Bozarth, 1987). Finally, under conditions involving motivated defense behaviors, serotonin appears to have an anxiolytic effect (Graeff et al., 1997), consistent with the hypothesized shut down of the security motivation loop – specifically its anxiety output (see Fig. 1).

3. Physiology of the security motivation system

The activity of the foregoing neural-circuit system occurs together with and in the context of wider physiological changes that prepare and facilitate appropriate responses. In a sense, every motivational system not only has its particular neural network but also possesses a characteristic physiology. Moreover, knowledge of this physiology can provide experimentally valuable markers to index the activity of the security motivation system, providing another window into the activity of the system, in addition to that provided by the monitoring of behavior.

We outlined above a plausible SMS neural circuit based on the notion that security motivation would have similar design features as other motivational systems. We follow the same logic here in proposing that the physiology of security motivation should possess features found in other motivational systems. However, there are also differences among motivational systems in terms of their physiology, as for example, when sexual motivation is engaged compared to hunger motivation. Hence, while not unique to it, security motivation should possess a characteristic physiology in terms of endocrine and autonomic activities.

What is the needed physiology to support an activated security motivation? SMS is turned on by potential threat, and as such it is geared for action—for doing *something* that will relax the psychological tension of uncertain danger. Hence, the needed physiological resources for security motivation include those that will mobilize energy for physical work and those that will specifically potentiate psychological mechanisms for threat detection.

In terms of physical workload, motor activity engendered by security motivation – for example, checking for predators – is not physically strenuous and hence not highly demanding of energy resources. However, there is the possibility that potential danger can quickly become real, which would necessitate high energy for fight-or-flight. Hence, it makes sense that to meet this possibility the physiological mechanisms for energy delivery are mobilized by security motivation into a state of high preparedness. However, while the security motivation system gears up energy supply mechanisms, it does not fully engage them in fuel delivery because responding to potential threat involves precautionary and probing behaviors, not requiring strenuous muscular effort.

Turning to the psychological mechanisms for threat detection, their enhancement probably follows the generic mechanism of motivational systems where peripheral physiology associated with a specific motivation serves also to potentiate brain processes appropriate to the motivation. For instance, in the case of sexual motivation, endocrine and autonomic activities serve to prepare the body for reproduction and at the same time facilitate sexual interest and sexual behavior, thus coordinating these component processes for optimal reproductive success (Beach, 1981; Komisaruk and Diakow, 1973; Szechtman et al., 1985; Zemlan and Adler, 1977). Similarly, in the case of security motivation, we can expect that the same physiology which mobilizes energy supply mechanisms should play a role also in potentiating brain mechanisms for threat detection and security-related behavior.

Which physiological mechanisms meet the above considerations for security motivation? We reason below that these physiological mechanisms operate though regulation of the parasympathetic nervous system and through activation of the hypothalamic–pituitary–adrenocortical (HPA) axis.

3.1. Autonomic regulation

The autonomic nervous system (ANS) is divided into a sympathetic system and parasympathetic system, with the two components generally working in opposition to each other to regulate the function of internal organs, including the heart and lungs. The classic conception is that parasympathetic activity serves to promote bodily functions related to growth and build up of energy resources while sympathetic activity promotes the converse, catabolizing energy stores and mobilizing body metabolism for a rapid and intense muscular exertion. Walter Cannon considered sympathetic activation as reflecting "... biological adaptations to conditions in wild life ... the necessities of fighting or flight" (Cannon, 1927, p. 211). He interpreted the sympathetic discharge as a "fight-or-flight" response to imminent threat because the evoked bodily changes made strenuous muscular exertion possible:

> The researches here reported have revealed a number of unsuspected ways in which muscular action is made more efficient [with sympathetic activation] ... Every one of the visceral changes that have been noted—the cessation of processes in the alimentary canal (thus freeing the energy supply for other parts); the shifting of blood from the abdominal organs, whose activities are deferable, to the organs immediately essential to muscular exertion (the lungs, the heart, the central nervous system); the increased vigor of contraction of the heart; the quick abolition of the effects of muscular fatigue; the mobilizing of energy-giving sugar in the circulation—every one of these visceral changes is *directly serviceable in making the organism more effective in the violent display of energy which fear or rage or pain may involve* (Cannon, 1927, p. 215–216, italics in original).

Clearly, sympathetic discharge is not the physiology of security motivation since SMS does not demand a "violent display of energy." Nonetheless, the work of security motivation is not consistent with a dominance of parasympathetic activity either. Activation of the parasympathetic system is generally suppressive upon sympathetic effects and serves to promote replenishment of energy stores ("rest-and-digest"); its activity is conducive for calm, non-threatened interactions in a safe environment (Porges, 1995a; Porges, 2001; Porges, 2009b). Security motivation calls for something in-between activation of the sympathetic system and activation of the parasympathetic system: it calls for a physiological state of high readiness to quickly support maximal effort should this be needed, while at the same time servicing small metabolic needs of ongoing behavior.

The autonomic nervous system can indeed produce such a physiological state, as elucidated in the Polyvagal Theory proposed by Porges (1995b, 1998, 2001, 2003, 2007b, 2009a). Reviewing the phylogenetic organization of the autonomic nervous system, Porges noted three developments in evolution of autonomic control over the viscera, and in particularly over the heart, a key vehicle in the distribution of metabolic resources:

> First, there is a phylogenetic shift in the regulation of the heart from endocrine communication to unmyelinated nerves, and finally to myelinated nerves. Second, there is a development of opposing neural mechanisms of excitation and inhibition to provide rapid regulation of graded metabolic output. Third, with increased cortical development, the cortex exhibits greater control over . . . visceral neural pathways (Porges, 2001, p. 129).

Of particular relevance for security motivation is the evolution of vagal regulation over cardiac output. As described by Porges (1995b, 2001), the vagus nerve (a component of the parasympathetic system) underwent marked phylogenetic development in its structure as well as in its control by the nervous system. Whereas in fish, amphibians, and reptiles, the vagus nerve originates in one brainstem region – the dorsal motor nucleus of the vagus – and consists of unmyelinated axons innervating the viscera, the mammalian vagus contains two branches and has two brain sites of origin. One site, the dorsal motor nucleus of the vagus (DMX), is the same as in the phylogenetic stage preceding mammals and gives rise to vagal unmyelinated efferents that project to digestive viscera. However, in mammals, the DMX does not send as many vagal projections to the heart. Instead, the heart is innervated by the second vagal branch, a branch which makes its appearance in mammals. This branch consists of myelinated axons with cell bodies of origin located ventrally and laterally to DMX—in the nucleus ambiguus (the "ambiguity" refers to the difficulty of early anatomists in demarcating the boundaries of this nucleus). Vagal projections to the heart from the right nucleus ambiguus are cardioinhibitory and play the following role in the physiology of security motivation.

As elaborated in the Polyvagal Theory (Porges, 1995b, 2001), vagal neurons in the right nucleus ambiguus send myelinated axons that innervate the sino-atrial (SA) node of the right atrium of the heart. The SA node is a pacemaker site that normally determines the rhythm of the heart. While these specialized cells undergo spontaneous generation of action potentials at a rate of 100–110 action potentials ("beats") per minute, resting heart rate in the human is lower, about 60–80 beats/min, due to a dominance of the cardioinhibitory vagal effects over sympathetic influences at rest. However, there are several distinct autonomic mechanisms that dynamically regulate heart rate and other pump properties of the heart. The Polyvagal Theory conceptualizes that these mechanisms are organized according to a phylogenetic hierarchy, with mammals adding new ones on top of the earlier ("reptilian") ones. These newer mechanisms evolved to deal with the mammalian biological adaptation of having an intrinsically high metabolic rate and being vitally dependent on oxygen, both uncharacteristic of reptiles. One such newer mechanism is the "respiratory sinus arrhythmia" (RSA), and it is highlighted here because a compelling case can be made that regulation of RSA reveals activation of security motivation.

In the Polyvagal Theory, there are four modes of parasympathetic-sympathetic functioning, organized hierarchically along a dimension of safety to dangerousness as follows. The highest ranking mode of operation is characterized by a dominance of parasympathetic influence, engaging a specially developed set of neural mechanisms that facilitate social interactions; these mechanisms can operate in an environment safe from dangers. Porges labels this brain state of facilitated perceptual and motor responses pertinent for social interactions as the"Social Engagement System," a system that has its own distinct neuroanatomy and physiology (Porges, 1998, 2001) (this system is similar to our postulated "safety" system). Moving along the hierarchy, the next stage is one in which the organism is directed to attend to the environment because of novelty or potential threat—this is the stage which is equivalent to activation of security motivation. In this stage, vagal influences over viscera (including the heart and the lung) are attenuated, and by so removing the antagonistic parasympathetic influence, the sympathetic system can be set off quickly if later needed. Sympathetic activity is mobilized in the next stage, when danger is imminent and the flight-or-flight set of responses are needed. Finally, when danger is life-threatening but flight-or-flight behaviors are not an option, then in the most primitive stage vagal activity controlled by the DMX becomes dominant, triggering immobilization responses such as "death feigning" and profound slowing of the heart and breathing (Porges, 1998, 2001).

Not only does the novelty/potential-threat stage of autonomic function represent the proposed requirements of a security motivation physiology, but this autonomic stage can be also measured objectively, by monitoring specific changes in heart rate variability. Normally at rest, the interval between heart beats is not constant but varies from beat to beat. This normal variation in inter-beat intervals is known as "heart rate variability." The time between two successive beats (generally measured in msec as the interval between the peaks of the R wave in the electrocardiogram; R-R interval) is the "heart period." The time series of R-R intervals shows several wave-like oscillations. The oscillations which are restricted to the frequencies associated with spontaneous breathing – in adult humans, those falling within the frequency band of 0.12 and 0.4 Hz – are known as the respiratory sinus arrhythmia (RSA) (Denver et al., 2007; Porges, 2007a). It is the RSA part of heart rate variability that can provide a window on transitions between the safe and the novelty/potential-threat autonomic stages, and thus index activity of security motivation.

The neurophysiological rationale for why changes in RSA can index security motivation, better than heart rate for instance, is compelling. As elaborated by Porges (2007a), RSA is a measure of neural activity in the "nucleus ambiguus-vagal circuit," a circuit which exerts an inhibitory influence over the cardiac pacemaker. Porges (2001) likened the inhibitory vagal influence to a "vagal brake" that restrains the heart from beating at its intrinsically higher rhythm, and the "removal of the vagal brake" to a withdrawal of the vagally-mediated perturbation of the pacemaker rhythm. Functionally, "removal of the vagal brake" is equivalent to a reduction in heart rate variability, as the time between heart beats is less modulated and thus more regular. Because the inhibitory vagal influence operates at the rhythm of spontaneous respiration and is modulated by it, there are two neural mechanisms contained within RSA. One reflects the operation of a rhythmical medullary network generating respiratory drive—this process is reflected in the frequency of RSA. The second one reflects the nucleus ambiguus-vagal impact on the cardiac pacemaker—this process is reflected in the amplitude of RSA. Since RSA amplitude is an expression of variance in R-R intervals (in units of ln msec^2), higher amplitudes indicate greater heart rate variability—relatively high variability being the normal state of a fully engaged parasympathetic system in a safe environment (Porges, 2007b). Accordingly, the proposed autonomic state of security motivation, that is, a shift from the safe to the novelty/potential-threat autonomic stage, is equivalent to a shift in RSA to lower variability. Thus, observed changes in RSA towards less variability are consistent with activation of security motivation. RSA change is a relatively pure index of vagal brake removal, unlike heart rate, which is influenced by vagal, sympathetic, and mechanical factors.

Supporting this hypothesis about RSA change as a marker of activation of the security motivation system, we conducted a series of experiments in which we showed that RSA change is a sensitive indicator of response to the potential threat of contamination (Hinds et al., 2010). In addition, as expected, RSA returns promptly to baseline once participants are allowed to engage in security-related behavior (hand washing). Note that it is RSA change from baseline, rather than the RSA level itself, that indexes activation of the security motivation system.

3.2. Physiology of security motivation: HPA axis

We enumerated two requirements for a physiology of security motivation: it should put the body into a state of quick readiness for maximal exertion, but without mobilizing those resources into action; and it should facilitate brain processes involved in the security motivation system. We discuss here that both of these requirements are met by a perturbation of the HPA axis, in that HPA hormones so released promote metabolic processes that mobilize energy reserves into a readily usable form and those same endocrine factors act on neural sites that are also components of the proposed security-motivation-system circuit. Below, we first provide examples that potential threat cues do indeed activate the HPA axis and then in turn consider the energy preparedness and the neural facilitation effects of HPA activation.

It is well recognized that bodily injury and many types of infection are associated with profound stimulation of the HPA axis and glucocorticoid (GC) secretions (Dhabhar, 2009; Sapolsky et al., 2000). However, besides such types of "physical" or "systemic" stimuli, the HPA axis can be stimulated also by events that are psychological in nature. In other words, the impact of the stimulus is derived from a psychological appraisal of the event by the organism. Stimuli of this sort are called "anticipatory" (Herman et al., 2003), "psychogenic stress" or "psychogenic stressors" (Pecoraro et al., 2006; Sapolsky et al., 2000). We highlight here several psychogenic stressors that we interpret as cues of potential threat able to activate security motivation.

A characteristic of cues of potential danger is that they constitute a subtle fraction of the complex of imminent threat (Szechtman and Woody, 2004). One such cue activating security motivation is presumably the mere odor of a predator since it should evoke vigilance and precautionary probing as to the source of odor: is there a predator hiding nearby? Indeed, odors of predators do elicit HPA activation in prey animals, even in laboratory rats who were never exposed to their natural predator, suggesting a biological predisposition. For instance, the smell of cats, ferrets, or foxes produces release of adrenal hormones in rodents (Anisman et al., 2001; Blanchard et al., 2008; Dielenberg and McGregor, 2001; Fendt and Endres, 2008; File et al., 1993; Masini et al., 2009; Takahashi et al., 2005; Weinberg et al., 2009). Similarly, animals recognize the smell of infected individuals (Kavaliers et al., 2005), which is conceivably associated with release of adrenal hormones.

While predator odors are a rather obvious example of a potential danger cue, SMS is designed to respond even to more subtle and generic indicators of potential danger. As noted in Fig. 1, appraisal of potential danger involves the evaluation not only of stimuli, but also a consideration of the current situation ("context") and future scenarios ("plans"). Accordingly, a most generic signal of potential threat is uncertainty that is created by virtue of exposure to novelty, for instance, an unfamiliar territory. This is in fact a very reliable procedure to stimulate a robust release of adrenal GC in rats, namely, transfer of the animal from its home apparatus to a new (empty) environment (Brown and Martin, 1974; Hennessy and Levine, 1978; Szechtman et al., 1974). Presumably the biological roots of a novel environment constituting potential danger are related to greater vulnerability of attack away from the home territory. Most likely, it is uncertainty which is the key element of this potential threat, because once the novel procedure becomes predictable through repeated exposure, the stimulus is no longer effective in producing an HPA response (Bassett et al., 1973; Mason, 1968; Pfister, 1979).

Potential loss of food resources is likely also an effective trigger of the HPA axis. This is suggested through the series of elegant studies with the "successive negative contrast" procedure by Pecoraro and colleagues (Pecoraro et al., 1999, 2006, 2009). In this procedure, different groups of food-restricted rats are allowed to drink one of two solutions of sucrose, 32% or 4%. Once a stable intake is established in which the 4% and 32% groups drink similar volumes of the sucrose solution, the 32% group is presented with the 4% solution to drink. This one change alone – a less sweet tasting solution – is sufficient to evoke a robust release of pituitary ACTH and adrenal corticosterone hormones (Pecoraro et al., 2009). That this phenomenon may reflect the activation of security motivation by potential threat is suggested by the rats' behavior. The downshifted rats engaged in very little drinking of the 4% sucrose solution, and instead engaged in a "repertoire of functional behaviors related to finding food" (Pecoraro et al., 1999). Clearly, an actual loss of food resources did not occur since a 4% solution was readily available. We suggest that what diverted the rats from the available sucrose towards probing the environment is an activated security motivation, which was stimulated by the potential threat of food depletion. The basis for the appraisal of potential food depletion is likely the present taste indicating less plentiful nourishment compared to the memorial taste of the food supply. Our suggestion that the downshift to a less sweet solution activated security motivation is consistent with the authors' own conclusion that "the suddenness, robustness, and reliability of the activation, along with the fact that these responses are not explicitly conditioned, are suggestive of a classical fixed action pattern released by a sign-stimulus" (Pecoraro et al., 2009, p. 660). Interestingly, an up-shift from 4% to 32% does not ramp up consumption beyond the rats' normal intake (Pecoraro et al., 2006), consistent with the notion that it is the threat of depletion which reduces sucrose consumption (rather than any type of "surprise") (Pecoraro et al., 2006).

Other types of psychogenic stressors are also known to perturb the HPA axis. For instance, potential threats to social standing, such as the mere act of speaking in front of an audience who are evaluating the speaker, are sufficient to produce a robust activation of adrenal hormones (Bosch et al., 2009). More generally, the potential threat associated with uncertainty of one's position in a social group is a likely trigger of HPA activity, given the conclusion of Sapolsky and colleagues that "an unstable position in a dominance system is a potent stimulus of GC secretion" (Sapolsky et al., 2000). Interestingly, threat to social standing can occur not only because of status issues but also because of a suspicion that the individual may be infected (see Neuberg et al., 2011), a potential threat that in many animal species results in "peripheralization" of the individual, keeping the animal at the peripheral borders of the group's territory (Hart, 1990). In summary, a wide variety of psychogenic stressors that are related to potential danger active the HPA axis.

3.3. Peripheral and central effects of HPA activation

The HPA response to a psychological stimulus has a prototypical pattern: Within seconds of stimulus presentation and appraisal as a "stressor" (potential danger), hypothalamic neurons of the paraventricular nucleus (PVN) secrete corticotropin-releasing hormone (CRH) into the portal circulation of the anterior pituitary lobe, where CRH triggers the release of pituitary ACTH into the systemic circulation. ACTH in turn stimulates the adrenal cortex to secrete glucocorticoids (GC); plasma glucocorticoids levels become elevated within 3–5 min and reach their peak at about 15–30 min

after stimulus presentation. The rising levels of glucocorticoids supply a negative feedback signal that inhibits CRH and ACTH release, and consequently plasma glucocorticoids levels return to baseline normally within an hour of stressor presentation.

Glucocorticoids are so named because their preeminent effect is to increase circulating glucose concentrations, the major fuel needed in cellular work including that of the brain and muscles. In fact, glucocorticoids are known to facilitate a myriad of mechanisms which result in increased energy availability. For example, glucocorticoids potentiate sympathetic effects on the cardiovascular system without producing an actual sympathetic activation; inhibit glucose transport into storage; synergize with catecholamines, growth hormone, and glucagon to stimulate lipolysis; and stimulate glycogenolysis and gluconeogenesis to elevate circulating glucose concentrations (Sapolsky et al., 2000). Because some effects require minutes to hours of exposure to glucocorticoids and are contingent on other processes, what is most pertinent for a physiology of security motivation are the immediate effects of glucocorticoids (e.g., potentiation of cardiovascular sympathetic effects; inhibition of glucose storage). However, if potential danger does turn into an actual threat, the later effects of glucocorticoids are more readily mobilized because of the prior period of glucocorticoids stimulation from an activated security motivation.

Sapolsky and colleagues distinguish between two classes of glucocorticoids actions: "modulating actions, which alter an organism's response to the stressor; and preparative actions, which alter the organism's response to a subsequent stressor or aid in adapting to a chronic stressor" (Sapolsky et al., 2000, p. 57). With regards to security motivation, we suggest that both modes of action are operative, in that the immediate effects of glucocorticoids are proposed to support the physiological needs of an activated security motivation, while at the same time the rise in glucocorticoids will serve to prime and prepare the physiological mechanisms needed in the case of a second stressor, imminent threat. Interestingly, the preparative actions of HPA activation are not confined to peripheral metabolism but extend also to a sensitization of brain processes, as indicated below.

Molecules which are key in HPA activity – CRH and glucocorticoids – are also likely key players in brain processes subserving security motivation. This is suggested by two kinds of evidence: neural sites proposed to subserve security motivation influence PVN activity as well as being modulated by CRH and glucocorticoids; and behavioral effects of CRH and glucocorticoids correspond to those expected of an activated security motivation.

The brain regions proposed as components of the Appraisal of Potential Danger Loop (Fig. 2) – namely, the amygdala, bed nucleus of the stria terminalis, hippocampus, and the medial prefrontal cortex – are also implicated in regulating the HPA response to psychogenic stressors (Herman and Cullinan, 1997; Pecoraro et al., 2009; Sullivan and Gratton, 2002; Ulrich-Lai and Herman, 2009), suggesting that the two processes may be closely related. Moreover, these and other components of the security-motivation-system circuit contain receptors for CRH and glucocorticoids (Joels and Baram, 2009; McEwen, 2007) and therefore are subject to regulation by an activated HPA.

With regards to functional effects on behavior, CRH and glucocorticoids affect behavior in a manner that is commensurate with an activated security motivation. Specifically, as noted below, these hormones potentiate brain mechanisms that: (1) heighten arousal and vigilance; (2) enhance detection and analysis of threat cues; and (3) facilitate future responding.

Administration of CRH into the brain of animals induces behavioral activation (Britton et al., 1986; Dunn and Berridge, 1990; Sutton et al., 1982; Winslow et al., 1989) and signs of electrophysiological cortical arousal (Curtis et al., 1997; Dunn and Berridge, 1990), consistent with the expectation that mediators of HPA activity play a role in potentiating brain mechanisms relevant for security motivation, such as arousal and vigilance. This potentiation may involve CRH action on locus coeruleus norepinephrine neurons, given that locus coeruleus modulates arousal (Aston-Jones and Cohen, 2005; Berridge and Waterhouse, 2003) and receives CRH projections from the amygdala (Joels and Baram, 2009; Valentino and Van Bockstaele, 2008), and given that potential threat increases activity in both regions (Liddell et al., 2005; Zald, 2003). Also of relevance to security motivation is the type of effect that CRH can produce; namely, it shifts locus coeruleus activity towards a tonic mode of neuronal firing, a mode of operation that has been proposed to be optimized for the scanning and sampling of the environment (Aston-Jones and Cohen, 2005; Joels and Baram, 2009; Valentino and Van Bockstaele, 2008). This operational mode induced by CRH should enhance detection and analysis of threat cues, and as such reflects a security-related brain mechanism potentiated by mediators of HPA activation.

CRH may also facilitate mechanisms for threat detection indirectly. Specifically, states of anxiety yield an attentional bias towards cues of threat (Cisler and Koster, 2010) and CRH induces anxiety by acting on the limbic system (Davis, 1998; Muller et al., 2003; Sajdyk et al., 1999). Activation of security motivation is proposed to trigger anxiety through a mechanism involving limbic structures (Szechtman and Woody, 2004). Consequently, CRH release by security motivation may serve to facilitate the mechanisms of anxiety, shifting attentional focus towards potential threat.

Other security motivation brain mechanisms potentiated by HPA mediators may involve the hippocampus. The hippocampus is rich with receptors for CRH and for glucocorticoids. Both subtypes of CRH receptors – CRHR1 and CRHR2 – are present in the hippocampus, as are both subtypes of receptors for glucocorticoids, mineralocorticoid receptors (MR) and glucocorticoid receptors (GR), with the two subtypes of each receptor often mediating functionally opposite effects (de Kloet et al., 2009; Joels and Baram, 2009). The actions of CRH on the hippocampus precede those of glucocorticoids not only because adrenal release of glucocorticoids lags minutes behind brain release of CRH (Chen et al., 2004; Korosi and Baram, 2008; Merali et al., 1998) but also because peak levels of glucocorticoids in the hippocampus are 20 min delayed compared to peak levels in plasma (Droste et al., 2008). The time scale of actions by CRH and glucocorticoids spans from seconds to hours, with the rapid effects involving membrane-bound receptors affecting cell excitability while the longer effects involving nuclear receptors to initiate a genomic signaling cascade with minutes to hours for completion (de Kloet et al., 2009; Joels and Baram, 2009). Differences in receptor subtypes and differences in the times of action of CRH and glucocorticoids may serve different aspects of security motivation function subserved by the hippocampus. We suggest two such plausible security related functions involving the hippocampus and modulated by CRH and glucocorticoids, as follows.

One function may involve future-oriented analysis. Specifically, because security motivation is activated by fragmentary cues of threat, probing for possible danger may involve the creation of mental scenarios in which such vague signs materialize as real threat (Abed and de Pauw, 1998; Brune, 2006)—in essence, to imagine the future. In a recent review article examining the neural role of the hippocampus, Buckner (2010) considers the adaptive function of memory systems as facilitating "predictions about upcoming events" (p. 27) and convincingly describes the evidence for an essential role of the hippocampus in envisioning future events. Such a functional role for the hippocampus is consistent with the workings of security motivation, and we hypothesize here that given the rich hippocampal distribution of receptors for CRH and glu-

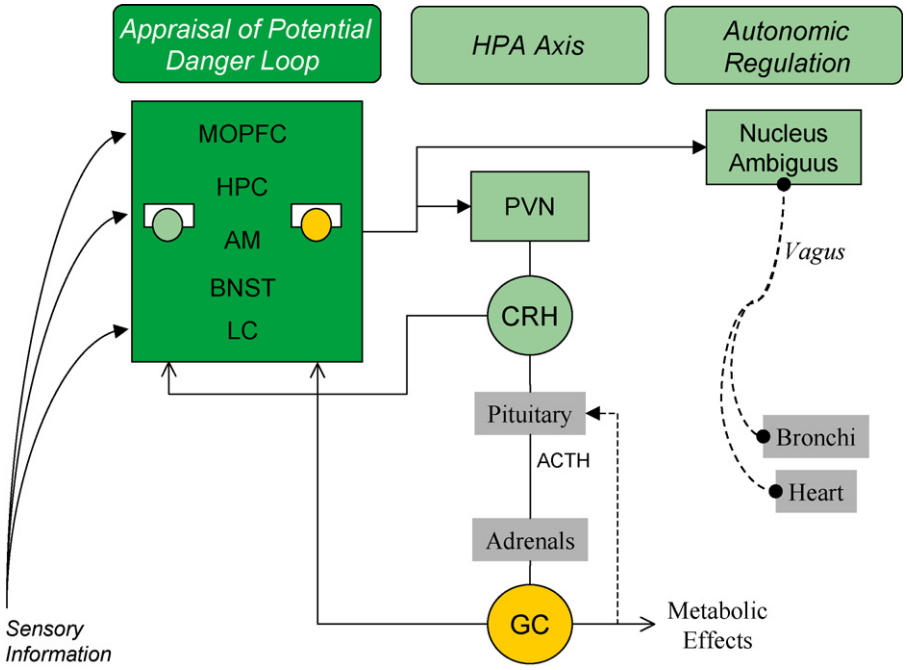

Fig. 3. The physiological network associated with security motivation. The Appraisal of Potential Danger Loop of Fig. 2 connects with the HPA Axis, which has both input from and output to the Appraisal Loop. Within the Appraisal Loop there are receptors for CRH and GC, denoted by the respective circles in white rectangles, by which HPA can modulate it; CHR also acts as a neurotransmitter within the Appraisal Loop. Finally, the Appraisal Loop affects Autonomic Regulation, by which the myelinated vagus modulates the bronchi and heart.

cocorticoids, HPA mediators are likely to modulate this type of threat-related appraisal.

Another hippocampal function likely of pertinence to security motivation is feedback inhibition of the HPA response. The hippocampus is involved in regulating the release of adrenal glucocorticoids to psychogenic stressors in that circulating glucocorticoids may act on the hippocampus to limit or terminate HPA activation (de Kloet et al., 1998; Herman and Mueller, 2006; Sapolsky et al., 1986). A crucial site for this suppressive regulation within the hippocampus may be the ventral subiculum as lesions there prolong the glucocorticoid response to a novel environment (Herman et al., 1998; Mueller et al., 2004). Such negative regulation may be of importance for terminating the activity of security motivation. As proposed, an activated security motivation is shut-down through performance of the appropriate precautionary behavior, and it will be important to determine whether such behavior synergizes with the actions of glucocorticoids to accelerate the shut-down of HPA activity. Moreover, it will be equally interesting to determine whether in the absence of effective precautionary behavior, security motivation remains activated until HPA stimulation is ultimately terminated.

As a closing possibility of HPA mediators facilitating brain mechanisms for detection and analysis of potential threats, we consider a form of learning that may be characteristic of security motivation, namely, sensitization. Because security motivation is geared for uncertain events, opportunities for learning are limited, as we noted at the outset of this paper. In such circumstances it makes adaptive sense to promote non-associative learning – sensitization – wherein the activation of security motivation by potential threat enhances the sensitivity of the system to subsequent instances of potential danger. Activation of HPA by psychogenic stressors also shows sensitization, in that following one episode of HPA activation, there is enhanced sensitivity to a subsequent unpredictable perturbation (Dallman, 1993; Herman and Mueller, 2006). This sensitization of the HPA response is a centrally mediated event, and may involve changes in a neural network including the hippocampus, amygdala, bed nucleus of the stria terminalis and the locus coeruleus, as well as a shift in the basal secretion of adrenal hormones (Choi et al., 2008; Dallman, 1993; de Kloet et al., 1998; Mueller et al., 2004). This neural network is involved also in mediating security motivation (Fig. 2), and hence a sensitized HPA response to psychological stressors may share mechanisms of sensitization to potential threats.

Fig. 3 summarizes the foregoing physiological networks. To the left, the Appraisal of Potential Danger Loop is carried over from the neural circuit model of Fig. 2 but incorporating the locus coeruleus based on its involvement in arousal as considered above. The central column of Fig. 3 depicts the HPA axis and its input from and output to the Appraisal Loop, as well as the metabolic effects of its activation. The column to the right represents Autonomic Regulation accompanying security motivation. Specifically, it depicts the role of the nucleus ambiguus in mediating input from the Appraisal Loop to the vagus nerve, which in turn affects the bronchi and heart.

4. Pathologies of the security motivation system

If, as we argue, there is a neural system dedicated to the assessment and management of potential risk, then it stands to reason that dysfunction in this system should produce characteristic forms of psychopathology. As mentioned earlier, some patterns of disordered behavior may reflect dysfunction in how the activity of the system is initiated, sustained, or terminated.

4.1. Obsessive-compulsive disorder

In particular, we have advanced the hypothesis that the symptoms of obsessive-compulsive disorder (OCD) may be understood in terms of the dysfunctional operation of the security motivation system (Szechtman and Woody, 2004; Woody and Szechtman, 2005). These symptoms involve recurrent, persistent thoughts (obsessions) and repetitive, ritualistic behaviors (compulsions), both typically connected to the theme of protection of self and others from potential danger. For example, patients with OCD may check for potential harm or wash to prevent contamination exces-

sively and repeatedly. In addition, patients with OCD experience such thoughts and behaviors as peculiarly intrusive and urgent, even though they typically appraise them as irrational and excessive.

We considered two different ways to explain such pathological intensity and persistence of security-related behavior: a starting problem, in which there is pathological intensity of excitation of the system by stimuli; and a stopping problem, in which there is failure of the normal process of termination of such security-related thoughts and actions (Szechtman and Woody, 2004). Building on the work of Reed (1977, 1985), we argued that characterizing OCD as a pathology of stopping better characterized the behavioral profile of the disorder. However, rather than conceptualizing OCD in terms of a general underlying cognitive disability to achieve closure, as Reed did, we posited that OCD results from the breakdown of a specific satiety-like mechanism by which engagement in security-related behavior normally shuts down the security motivation system (cf. Zald and Kim, 2001). Phenomenologically, this stopping mechanism is associated with an internally generated satiety-like signal that serves as a terminator for the primal motivation concerning potential danger. As mentioned earlier, we called this specific, internally generated signal *yedasentience*. We stated our core hypothesis about OCD as follows:

> An internally generated feeling of knowing (termed yedasentience) provides a phenomenological sign of goal attainment and has as its consequence the termination of thoughts, ideas, or actions motivated by concerns of harm to self or others. Failure to generate or experienced this feeling produces symptoms characteristic of OCD (Szechtman and Woody, 2004, p. 116).

In terms of the schematic model shown earlier in Fig. 1, the hypothesized dysfunction is a blockage in the feedback loop linking the Motor and Visceral Output component to Yedasentience. The result of this blockage is that the performance of security-related behavior would fail to inhibit the Security Motivation and Appraisal of Potential Danger components in the normal way. Without the terminator for these species-typical programs, they would continue with abnormal intensity and persistence, yielding the behavioral profile of OCD.

Another possible blockage would be from the Security-Related Programs component to the Motor and Visceral Output component. The result of this blockage would be the failure to initiate the species-typical acts upon which the security motivation system relies for inhibitory feedback. We suggested that this second type of blockage may yield the pure-obsessional subtype of OCD (Emmelkamp and Kwee, 1977; Salkovskis and Westbrook, 1989; Steketee, 1993; Stern, 1978).

In terms of the neural-circuit model shown earlier in Fig. 2, our hypothesis about OCD locates the basic dysfunction in the failure of the Brainstem Output Network to serve adequately as a terminator of the activity of the Security Motivation and Affect Loop and, in turn, the activity of the Appraisal of Potential Danger Loop. As a consequence, reverberating activity in these loops persists abnormally.

Finally, we have hypothesized that in OCD other important problems in cognition and behavior may eventually develop as secondary elaborations of this core, primary deficit (Woody and Szechtman, 2005). In particular, because security-related acts, together with the satiety-like feeling they would normally evoke, do not work for patients with OCD, they likely attempt to compensate by substituting cognitions (i.e., obsessions) for behavior. Another important secondary effect is the development of avoidant and precautionary behaviors that help to prevent the activation of the security motivation system in the first place. That is, given difficulty in shutting down security motivation once it has become activated, patients with OCD may learn to avoid stimuli that suggest danger and could potentially activate the system. They may also learn to engage in relatively frequent, smaller-scale prophylactic rituals that proactively help to prevent the system from becoming activated (see Eilam et al., 2011). These rituals need to be distinguished from repetitive behaviors that are driven by the attempt to shut down the system once it is activated.

The foregoing review of the physiological network associated with the security motivation system suggests several other useful hypotheses about OCD. First, uncertainty and disturbance of the familiar would perturb HPA, and if prolonged, such perturbations may alter the basal level of the diurnal secretion of glucocorticoids, thereby sensitizing cues for potential threat. Thus, instability in daily life would lower the threshold for activation of the security motivation system, exacerbating OCD symptoms. Indeed, a recent study showed that stress management works just as well as cognitive-behavioral therapy for ameliorating obsessions (Whittal et al., in press).

Second, the HPA axis provides an intriguing perspective for understanding the substantial comorbidity between OCD and depression (du Toit et al., 2001; Fireman et al., 2001; Tukel et al., 2002). If the OCD patient's behavioral strategies are chronically ineffective in preventing the activation of the security motivation system, then we would expect chronic HPA activity. Some evidence of altered HPA activity in OCD has been reported (Bigos et al., 2009; Gustafsson et al., 2008; Kluge et al., 2007). Continuing HPA activity will have many debilitating effects, including the development of depression (Holsboer and Ising, 2010; McEwen, 2007; Schulkin et al., 1994; Willner, 2005). Hence, the OCD patients who develop depression may be those in whom there is exaggerated HPA activity.

Third, the physiology of security motivation suggests ways in which early upbringing may predispose an individual toward the development of certain kinds of psychopathology through the calibration of the security motivation system (see Boyer and Bergstrom, 2011; see Lienard, 2011). Studies with animals have demonstrated that early-life experiences are a powerful determinant of life-long reactivity of the HPA axis (Arnold et al., 2007; Blas et al., 2007; Francis et al., 1999). Given that the operation of the HPA axis is integral with the security motivation system, early experience could have a substantial impact on later reactivity to potential threat and vulnerability to dysfunction of this system.

4.2. Other possible pathologies of the security motivation system and their relation to OCD

Recently there has been a vigorous debate about how OCD relates to other disorders. One proposal is that OCD should be removed from the anxiety disorders, and that a new category of obsessive compulsive-related disorders should be created (Hollander et al., 2008; Stein, 2008; see also Storch et al., 2008). Common across the proposed spectrum would be the theme of "repetitive behaviors and inability to resist impulses and urges" (Hollander et al., 2008, p. 317). Similarly, in a review of cross-species models of OCD spectrum disorders, Boulougouris et al. (2009) anchored their perspective on the theme of "motor habits suggestive of inhibitory dyscontrol" (p. 15).

Rather than an emphasis on themes such as repetitive behavior or poorly inhibited motor habits, we would suggest that a better way of organizing and understanding the relations among various psychopathologies would be to view them in terms of common underlying mental modules, such as the security motivation system. For example, as reviewed earlier, there is a large body of research supporting the hypothesis that potential danger and manifest danger are handled by different mental modules. In this way, OCD would be fundamentally distinct from anxiety disorders such as specific phobias. In contrast, we have suggested that just as

OCD can be conceptualized as a stopping problem in the operation of the security motivation system, generalized anxiety disorder (GAD) could be conceptualized as a starting problem in this system (Szechtman and Woody, 2006). That is, GAD, in which worry shifts restlessly from issue to issue, may reflect a starting malfunction in the Appraisal of Potential Danger component. If this is true, then GAD would be, like OCD, another pathology of the security motivation system, but stemming from a different type of dysfunction in the system than OCD. Szechtman and Woody (2006) discuss in more detail how the concept of a security motivation system may shed light on the relation of OCD to other psychopathologies and the problem of comorbidity.

5. Conclusion

In this article we have attempted to demonstrate the wide-ranging heuristic power of one core idea, which is this: To manage risks entailed by the possibility of events that are improbable but would have grave consequences, a special motivational system evolved. This system is designed to detect subtle and uncertain signs of potential threat to self and others, to motivate the probing and manipulating of the environment to acquire further information about such potential dangers, and to generate precautionary behavior that may help ameliorate the effects of such an event if it does occur. We reviewed a considerable body of work across many species indicating that the challenges organisms face from improbable and uncertain potential dangers are quite different from other challenges, such as those posed by manifest threats, and thus require a dedicated system, which we have termed the security motivation system.

Developing this core idea, we have decomposed the security motivation system into its functional components and proposed reasonably detailed neurobiological circuits subserving and interconnecting each of these components. Our model builds on the principle of functional loops involving cortico-striato-thalamo-cortical connections and incorporates a brainstem-mediated feedback mechanism to shut down activity in these loops. In addition, we proposed a wider network of physiological (autonomic and endocrine) mechanisms that play an important role in security motivation. One part of this physiological network involves the parasympathetic nervous system, including vagal regulation of the heart and the modulation of respiratory sinus arrhythmia, which, we argue, can serve as a physiological indicator of security motivation. Another part of the network involves activation of the hypothalamic–pituitary–adrenocortical axis, mediated by corticotropin-releasing hormone and glucocorticoids, which prepares physiological mechanisms needed to probe the environment and to respond if the potential threat eventuates. This axis also has a feedback effect on brain processes subserving security motivation.

Finally, we proposed that some psychopathologies may be conceptualized as disorders of the assessment and management of potential risk, and thus may stem from dysfunction of the security motivation system. In particular, we have hypothesized that obsessive compulsive disorder results from the failure of a satiety-like mechanism, such that security-related behavior that would normally terminate activation of the system fails to do so. We also proposed that a promising approach for organizing some psychopathologies and understanding comorbidity is to conceptualize pathologies in terms of common underlying modules, such as the security motivation system.

However, fulfilling such promise will require that we advance our knowledge of the security motivation system by developing a more detailed and differentiated understanding of its normal functions. In particular, potential threats such as contagion and predation pose quite different adaptive challenges and may be handled by distinguishable, although related, subsystems. For example, Hart (1990) proposed a set of specific behavioral adaptations to manage the potential threat of pathogens and parasites, and the operation of such subsystems likely includes the involvement of immune-brain pathways (Dantzer et al., 2008). Under the umbrella of the security motivation system, there are likely important clusters of behavioral adaptations for different subdomains of potential threats, and this is an important area for further study.

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