Dual Learning Systems Under Stress

Authors: Cheng Yizhi, Wu Yin, Li Hong, Li Hong

Date: 2018-12-27T00:00:00+00:00

Abstract

Numerous studies in psychology, neuroscience, and behavioral economics have consistently agreed that human behavior is controlled by a dual learning system, namely the reflexive system and the reflective system. The former is an automated habitual system that responds rapidly without consuming cognitive resources, whereas the latter is a slower cognitive system that requires more cognitive resources but is also more flexible and can effectively respond to changes in the external environment. These two learning systems exist in parallel and compete with each other, jointly influencing human psychology and behavior. Which learning system plays a dominant role in specific human behaviors and what factors lead to that system' s control over behavior are questions that have received widespread attention in recent years. Previous researchers have employed navigational learning, probabilistic classification learning, or instrumental learning and their computational models to investigate changes in the dual learning system under acute and chronic stress from both behavioral and brain levels. Through reviewing and analyzing these studies, we summarize the physiological mechanism by which stress leads to a shift toward habitual behavior in individuals, namely that norepinephrine and glucocorticoids, with the involvement of the amygdala, bind to receptors and act synergistically on brain regions related to the dual system, and from this perspective, we re-examine and explain the formation of drug addiction. Future research should focus on the relationship between individual genetic differences and stress' s impact on learning, and employ multiple research methods to better reveal the underlying neural and endocrine mechanisms.

Full Text

Dual-Learning Systems Under Stress

CHENG Yizhi[1]; WU Yin[1]; LI Hong[1],[2],[3]
([1] College of Psychology and Sociology, Shenzhen University;
[2] Shenzhen Institute of Neuroscience, Shenzhen 518060, China)

Abstract

Numerous studies in psychology, neuroscience, and behavioral economics converge on the view that human behavior is controlled by dual-learning systems: the reflexive system and the reflective system. The former is an automated habitual system that responds rapidly without consuming cognitive resources. The latter is a slower cognitive system that requires more cognitive resources but is more flexible and can effectively adapt to changes in the external environment. These two learning systems exist in parallel and compete with each other, jointly influencing human psychology and behavior. A question of widespread concern in recent years is which learning system plays a dominant role in specific human behaviors and what factors cause that system to govern behavior. Previous researchers have employed navigation learning, probabilistic classification learning, or instrumental learning tasks and their computational models to investigate changes in dual-learning systems under acute and chronic stress at both behavioral and neural levels. By reviewing and analyzing these studies, we summarize the physiological mechanism underlying stress-induced shifts toward habitual behavior, namely, that noradrenaline and glucocorticoids, orchestrated by the amygdala, bind to receptors and exert synergistic effects on brain regions related to the dual systems. From this perspective, we reinterpret the formation of drug addiction. Future research needs to focus on the relationship between individual genetic differences and stress effects on learning, and employ multiple methodological approaches to better reveal the underlying neural and endocrine mechanisms.

Keywords: stress; dual-learning systems; reflexive system; reflective system; drug addiction

---

1. The Dual-Learning Systems

1.1 Reflexive and Reflective Systems

Human beings and other organisms have evolved over millions of years to develop instincts for seeking advantages and avoiding harm in complex environments. A long-standing question among researchers is whether individual behavior represents simple responses to stimuli or is driven by anticipated outcomes. Numerous studies suggest that individuals are governed by dual-learning systems—the reflexive system and the reflective system—which coexist in the human brain and function either independently or in competition with each other across different contexts [?, ?, ?, ?, ?, ?, ?, ?].

The reflexive system, also known as the habitual system, is built upon stimulus-response associations. Characterized by automaticity, rapid responding, and minimal cognitive resource consumption, this system helps conserve mental energy for coping with other complex environmental demands, making it an adaptive learning mechanism. However, because the habitual system does not require individuals to explicitly contemplate the potential consequences of their actions, it tends to be rigid and inflexible, unable to adapt to changing external circumstances. The reflective system, also termed the cognitive system, is based on action-outcome associations and requires individuals to explicitly consider the potential consequences of their impending actions. Unlike the reflexive system, it responds more slowly and consumes greater cognitive resources, but offers greater flexibility in effectively addressing environmental changes.

1.2 Factors Influencing Dual-Learning Systems

Early research focused on providing evidence for the existence of dual-learning systems and dissociating them at behavioral and neural levels, accumulating a substantial body of findings. In recent years, research interest has shifted toward identifying factors that modulate the control exerted by these systems over behavior: which system dominates specific human behaviors and what factors cause such dominance have become increasingly important questions for investigators.

Studies indicate that for optimal task performance, the reflexive and reflective systems typically need to be simultaneously engaged in behavioral control [**?**, **?**, **?**, **?**, **?**, **?**]. However, in other contexts, numerous factors—including distraction tasks [**?**, **?**, **?**, **?**], training duration [**?**, **?**], and stressful events [**?**, **?**]—can influence and alter the dominant role of these two learning systems in guiding behavior. Take training duration as an example: washing hands before meals to avoid bacterial infection represents a goal-directed behavior controlled by the reflective system. Yet after this behavior is repeated numerous times, the reflexive system begins to dominate, such that individuals automatically wash their hands upon entering the kitchen without contemplating the purpose. This illustrates that normal behavioral performance results from a dynamic balance between the dual-learning systems, whereas overtraining disrupts this equilibrium. Stress can also affect dual-learning systems, primarily by reducing flexible cognitive strategies and increasing rigid habitual responses [**?**, **?**, **?**, **?**].

For instance, participants who experienced acute stress continued to respond for food rewards even when satiated, demonstrating habitual responding [**?**, **?**]. Stress can elevate cortisol levels, thereby promoting a shift from the reflective to the reflexive system [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]. This article will review accumulated findings to delineate the cognitive processes and neural mechanisms through which stress influences dual-learning systems.

2. Stress and Stress Responses

2.1 Definitions and Physiological Mechanisms

Stress is ubiquitous in daily life and exerts significant influence on mental health. Regarding the definition of stress, Koolhaas et al. (2011) concluded through meta-analysis that stress emerges when external stimuli exceed an individual' s regulatory capacity. Traditionally, stressors were considered uncontrollable and unpredictable, but a new perspective suggests that events that can be accurately predicted may also induce stress [?, ?, ?, ?].

Stress involves two physiological systems: the sympathetic-adrenal-medullary (SAM) axis and the hypothalamic-pituitary-adrenal (HPA) axis [?, ?]. These axes promote the secretion of catecholamines (including adrenaline and noradrenaline) and glucocorticoids, respectively, triggering a series of peripheral neural responses including changes in heart rate, blood pressure, and alpha-amylase secretion. Glucocorticoids can enter the brain and bind to glucocorticoid receptors (GRs) and mineralocorticoid receptors (MRs), thereby affecting cognitive function-related brain regions such as the prefrontal cortex. In humans, the primary glucocorticoid is cortisol, which elevates blood glucose levels to provide energy for behavioral responses.

2.2 Stress Induction Procedures

Based on the operational definition of stress, researchers design stressors to elicit stress responses in participants, timing experimental tasks to coincide with expected peak cortisol levels. The Socially Evaluated Cold Pressor Test (SECPT), developed by Schwabe et al. [?, ?], requires participants to immerse their hands in ice water while being videotaped, creating both physiological and psychological threats that effectively induce stress responses, such as significantly increased cortisol levels [?, ?]. Its simple experimental procedure makes it an economical and efficient stress induction paradigm. The Trier Social Stress Test (TSST) is also widely used [?, ?, ?, ?], requiring participants to deliver a public speech and perform mental arithmetic while being recorded, thereby adding social evaluative components. Ishizuka et al. (2007) demonstrated the validity of this paradigm. The group version of the TSST (TSST-G) [?, ?, ?, ?] enhances experimental efficiency. While the TSST is more effective at inducing stress, its relatively cumbersome procedure requires researchers to weigh trade-offs based on specific research objectives.

3. Dual-Learning Systems Under Stress

Researchers have induced stress in laboratory settings and employed navigation learning, probabilistic classification learning, instrumental learning, and their computational models to investigate the effects of stress on dual-learning systems, while attempting to uncover the underlying neuroendocrine mechanisms.

From navigation learning to computational models of instrumental learning, we briefly review research across these four domains, covering their theoretical origins, experimental paradigms, and logical frameworks, before delineating how stress and its mediating factors bias individuals toward particular learning systems in each area.

3.1 Navigation Learning

Research on navigation learning can be traced back to early 20th-century debates between stimulus-response theory and cognitive learning theory. Stimulus-response learning theory posits that rats learn to respond to stimuli in specific ways in a T-maze—for example, learning to turn right during the test phase to obtain food—because food reinforcement strengthens the stimulus-response association. Tolman, however, argued that rats do not learn a sequence of left or right turns but rather construct a "cognitive map" of the maze layout in their brains, which they use to navigate toward food. Results from the Plus-Maze Task support this latter view. This maze features two opposite entry points (north and south) and two distinct goal locations (east and west). Experimental mice were divided into spatial learning and response learning groups, entering the maze from different starting points to locate food. For the spatial learning group, food location varied across trials, whereas for the response learning group, food was consistently placed to the right of the entry point. Findings revealed that with increasing trials, the spatial learning group showed a rapid decline in error rates compared to the response learning group, demonstrating spatial learning capacity [**?**, **?**, **?**, **?**]. To behaviorally dissociate spatial learning from stimulus-response learning, researchers designed navigation learning tasks based on the plus-maze. Food was placed on the left side of the cross-maze, and during training, rats entered from the north entrance, ensuring all rats learned to obtain food by turning right. In the test phase, the entry point was switched to the south. If rats repeated the same action (turning right) due to training influence, this reflected stimulus-response learning. If they were unaffected by training and quickly made the opposite action (turning left), this reflected spatial learning control.

The first study to investigate stress-induced habituation using a navigation learning task was conducted by Kim et al. (2001). They administered electric shocks to experimental mice to induce stress responses, then had them perform the Morris water maze (MWM) task. Results showed that the stressed group exhibited shorter latencies to reach the new platform, with half the mice using a stimulus-response strategy by swimming directly to the new platform, while the other half first swam toward the original platform location before reaching the new one, suggesting spatial learning strategy. However, swimming distances between old and new platforms indicated greater reliance on stimulus-response strategies. To validate these animal findings, Schwabe et al. (2007) designed a novel spatial learning task to examine the effects of acute stress on dual-learning systems in human participants. The experiment presented a three-dimensional room model with four face-down cards on a central table, one of which was a “winning card”fixed in location next to a plant. The room’s walls contained cues such as doors, windows, and clocks. Participants learned to identify the winning card based on feedback from the experimenter. The experimenter rotated the room and swapped wall positions, but the winning card and plant remained fixed without informing participants. If participants learned that the winning card was always adjacent to the plant, this represented a stimulus-response strategy; if they learned the card’ s location through wall cues, this represented a spatial learning strategy. The study found that compared to controls, the stress group —who underwent the TSST 15 minutes prior and showed significantly elevated salivary cortisol—relied more on stimulus-response strategies and less on spatial learning strategies. These human results largely converged with Kim et al.’ s animal findings, demonstrating that stress enhances dorsal striatum-dependent habitual learning. Researchers further noted that adopting stimulus-response strategies under stress represents an adaptive response.

A recent neuroimaging study replicated these results [?, ?]. This study employed a virtual navigation task combined with an MRI-compatible SECPT, requiring participants to immerse their right foot in 0–2°C ice water for three minutes while performing difficult mental arithmetic, followed by the virtual navigation task. Behavioral results showed that stressed participants primarily relied on landmark cues, reflecting stimulus-response learning, whereas control participants depended on horizon cues, employing spatial learning strategies. Neuroimaging data revealed stronger amygdala activation and more active functional connectivity between the amygdala and striatum in the stress group. Additionally, pharmacological manipulation studies found that individuals who ingested MR receptor antagonists did not show these behavioral effects or significant brain region activation. This study directly demonstrates that MR receptors and the amygdala play crucial mediating roles in stress effects on learning systems.

Beyond acute stress, chronic stress and stress occurring during critical periods of brain development similarly bias individuals toward dorsal striatum-dependent stimulus-response learning [?, ?, ?, ?, ?, ?, ?, ?]. For instance, individuals whose mothers experienced negative life events during pregnancy—representing prenatal stress—showed greater use of rigid stimulus-response learning strategies in virtual navigation tasks during adulthood. This indicates that learning strategy selection is also significantly influenced by early-life stress.

3.2 Probabilistic Classification Learning

Building on the aforementioned research, investigators developed probabilistic classification learning, in which individuals learn probabilistic relationships between cues and outcomes across multiple trials to categorize stimuli. The Weather Prediction Task (WPT) is a widely adopted paradigm. In this task, four different cards serve as cues that predict two possible outcomes (sunny or rainy weather) with specific probabilities. Participants learn the predictive probabilities of single or multiple presented cards through feedback. Similar to the plus-maze task, WPT performance involves both hippocampus-dependent cognitive systems and dorsal striatum-dependent habitual systems, manifesting as explicit versus implicit strategies during category learning. Individuals using explicit strategies rely on a single cue—for example, judging it will be sunny whenever cue card 1 appears, and rainy otherwise. Those using implicit strategies first learn the predictive probability of each cue card, then integrate simultaneously presented cards to form cue patterns for weather prediction. Researchers use mathematical models to confirm which strategy individuals adopt. Studies have shown that the hippocampus is activated when using the former strategy, whereas the striatum is activated when using the latter [**?**, **?**], indicating that explicit strategies primarily involve the cognitive system while implicit strategies reflect habitual system control.

Consistent with navigation task studies, probabilistic classification task research has also found that stress reduces hippocampus-based learning and increases dorsal striatum-based learning biases [**?**, **?**, **?**]. Schwabe and Wolf (2012) used functional magnetic resonance imaging with the weather prediction task to investigate whether acute stress modulates the engagement of these two learning systems and their underlying neural mechanisms. Experimental group participants learned to predict weather from cue cards, while control participants simply pressed buttons to indicate whether fewer than two cards were displayed on screen, a task that did not involve learning. The experimental group underwent the SECPT, and all participants received MRI scans 25 minutes post-stress induction—when salivary cortisol levels were expected to peak—while performing the classification task. Results revealed that stressed participants more frequently employed multi-cue strategies, though task performance itself was unaffected by stress. Neuroimaging data showed striatal activation in the experimental group but hippocampal activation in the control group, providing the first evidence in humans that stress alters the neural mechanisms of dual-learning systems.

3.3 Instrumental Learning

As spatial learning may involve geometric cognition, spatial navigation tasks cannot be fully generalized to broader learning contexts, prompting researchers to focus on instrumental learning. Instrumental learning can be controlled by goal-directed systems with neural substrates in the orbitofrontal cortex and putamen, reflecting individuals' action-outcome associations where outcomes are desired or needed. Instrumental learning can also be governed by habitual systems based solely on stimulus-response associations, independent of outcomes, with the caudate nucleus as the primary associated brain region [**?**, **?**]. To dissociate whether an instrumental behavior is goal-directed or habitual, researchers have developed instrumental learning paradigms, most notably the outcome devaluation task [**?**, **?**, **?**, **?**], widely considered the gold standard for demonstrating habitual behavior. During training, participants learn associations between button presses and food rewards, with one button yielding high-probability food rewards and another low-probability rewards. In the devaluation phase, participants consume the food until satiated, eliminating motivation to obtain it. During the extinction test phase, participants resume button pressing. If they continue pressing the high-probability food button despite devaluation, they show outcome insensitivity, indicating habitual system control. If they cease pressing the devalued button, they demonstrate outcome sensitivity and motivation-guided choice, reflecting goal-directed learning control. Initially used in rodent brain lesion studies and later adapted for humans, this task has revealed that the orbitofrontal cortex and dorsomedial striatum underlie goal-directed behavior, while the dorsal striatum forms the neural basis of habitual behavior [?, ?, ?].

Studies of stress in mice have shown that rats stressed before outcome devaluation are insensitive to outcome value changes, exhibiting more habitual behavior compared to non-stressed controls [?, ?]. To investigate stress effects on human goal-directed learning, Schwabe and Wolf (2011) employed this instrumental learning task and found that during the test phase, stressed participants showed no change in button pressing, displaying more habitual behavior than controls. Notably, stress induction in this study occurred before the devaluation phase, potentially affecting learning during training. To avoid this confound, subsequent work placed stress induction after the devaluation phase and replicated these findings [?, ?]. In follow-up research, half of the stressed participants received a beta-adrenergic blocker (propranolol) to reduce stress-induced physiological responses, and the drug-treated group exhibited goal-directed behavior [?, ?, ?, ?, ?]. Goal-directed behavior following outcome value changes represents flexible, adaptive responding, and these findings suggest that stress impairs such adaptive behavior, possibly mediated by adrenal hormones. However, these results cannot resolve whether stress affects the goal-directed system, enhances the habitual system, or both. Addressing this issue, recent research found that stressed participants performed well on trials dependent solely on the habitual system, indicating that stress affects behavioral flexibility by acting on the goal-directed system rather than damaging the habitual system [?, ?, ?, ?].

Like hippocampus- or dorsal striatum-based learning, instrumental learning is also affected by chronic and early-life stress, shifting toward more habitual responding [?, ?, ?, ?, ?, ?, ?]. While most stress research on cognitive functions has focused on adult participants, fewer studies have examined early life periods. To address this gap, researchers developed an infant version of the instrumental learning task in which infants learned to press buttons [?, ?]. The experiment was manipulated such that two buttons that previously produced lights and sounds became devalued (no longer functional) during the test phase. Stressed infants, who underwent a three-phase stress protocol to effectively elevate salivary cortisol levels [?, ?], continued pressing the same button despite its loss of function, whereas control infants began exploring the alternative button after habitual pressing. This demonstrates that stress impairs cognitive flexibility in infants, preventing behavioral adjustment to changed environments. Soares et al. (2012) used neuroimaging to show that individuals experiencing chronic stress from prolonged medical exam preparation exhibited habitual behavior alongside structural and functional changes in the caudate nucleus and putamen. Longitudinal follow-up revealed that six months after exams, the formerly chronic stress group reverted to goal-directed behavior, indicating that chronic stress effects on brain structure and function are reversible—a finding with theoretical significance for clinical stress research. Together, these studies consistently demonstrate that acute, chronic, and early-life stress all strengthen individuals' habitual behavioral tendencies, regardless of whether behavioral or neuroimaging methods are employed.

3.4 Computational Models of Instrumental Learning

Through decades of development, the instrumental learning field has accumulated substantial research findings, leading to computational models of habitual and goal-directed behavior. Inspired by artificial intelligence and optimal control theory, Sutton and Barto (1998) proposed reinforcement learning (RL) theory, using computational and modeling approaches to study how individuals learn about their environment through trial and error to maximize reward while minimizing punishment. The most commonly used paradigm is the sequential decision task, which assesses the balance between model-based and model-free learning. Model-based learners must predict action outcomes in specific states, compare actual outcomes with predictions to generate prediction errors (PE), and update their internal model of the task—how different actions lead to different states or outcomes, and how these outcomes map onto values. Model construction facilitates evaluation of potential action values to guide subsequent choices. In contrast, model-free learners focus only on direct action values, maintaining actions that previously yielded pure rewards, increasing the likelihood of actions that produced rewards and decreasing those that produced punishments. Clearly, model-based learning is considered goal-directed, while model-free learning is deemed habitual [**?**, **?**, **?**, **?**, **?**, **?**]. In sequential decision tasks, stage one of each trial typically offers two distinct shapes, each with fixed probabilities of transitioning to stage two states. In stage two, participants again choose between two shape stimuli, receiving monetary reward or no-reward feedback, with reward probabilities varying within a certain range. Habitual learners always repeat stage-one shapes that previously yielded rewards, regardless of whether the stage-one-to-stage-two transition was common or rare. Conversely, goal-directed learners consider the task' s transition structure, selecting stage-one shapes that lead to common transitions and ultimately reward. Researchers use reinforcement learning computational models to derive the relative weights of model-based and model-free learning based on participants' choices.

Numerous studies show that under normal circumstances, learners in sequential decision tasks exhibit control by both systems [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]. Model-based learning consumes cognitive resources but offers flexibility, whereas model-free learning conserves resources at the cost of flexibility. These two systems exist in parallel and compete to jointly control behavior. However, factors influencing which system dominates behavior remain unclear. Researchers noted that working memory capacity depletion reduces reliance on model-based learning without affecting model-free learning [?, ?, ?, ?, ?]. Previous research has demonstrated that stress affects working memory and prefrontal brain regions associated with it [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?], leading to the hypothesis that stress selectively impairs model-based learning while sparing model-free learning. Otto et al. (2013) therefore employed the SECPT, inducing stress in participants ten minutes before they performed a reinforcement learning task while assessing cognitive abilities with working memory scales. Results supported the hypothesis: stress impaired model-based system utilization while leaving the model-free system unaffected. Furthermore, the study found that individuals with lower working memory capacity tended toward model-free learning under acute stress, whereas those with higher capacity could effectively avoid stress-induced model-free learning biases. Another study found that individual differences in stress responses predicted model-based learning impairments, with participants having high chronic stress levels showing reduced model-based control when facing acute psychosocial stress compared to those with low chronic stress [?, ?]. These findings indicate that working memory and chronic stress moderate the effects of acute stress on model-free learning tendencies. Future research must therefore fully consider individual differences in HPA axis responses and target cognitive training and stress management interventions in clinical applications to enhance stress coping abilities.

It should be noted that these four research traditions all developed within a dual-system framework, converging on the reflexive and reflective systems. In summary, we contend that regardless of learning type, experimental paradigm, or participant population, previous research has yielded consistent conclusions: stress induces a shift from cortex-based reflective systems to striatum-based reflexive systems, mediated by neurotransmitters and hormones such as noradrenaline and glucocorticoids.

---

4. Psychological Mechanisms of Stress Effects on Dual-Learning Systems

The psychological mechanisms through which stress influences dual-learning systems can be explained from the perspective of Pavlovian-Instrumental Transfer (PIT). Pavlovian conditioning, also known as classical conditioning, refers to the process by which a neutral stimulus becomes a conditioned stimulus after being paired with an unconditioned stimulus, thereby eliciting a specific behavior. For example, when a tone is paired with food, the animal learns to salivate or orient toward the food location upon hearing the tone. The primary difference between instrumental and Pavlovian conditioning is that the former requires active behavioral responses that are subsequently reinforced. For instance, rats must press a lever to obtain food, and this lever-press training can produce the two forms of instrumental behavior of interest in this article: habitual learning and goal-directed behavior. In the PIT paradigm, animals first undergo Pavlovian training (e.g., a light stimulus followed by food), then instrumental training (learning to press a lever for the same food reward). After training, food is removed, and animals are placed in a testing area with the lever while the light stimulus is presented, resulting in significantly increased lever-pressing frequency. This paradigm has also been applied to human participants to investigate how conditioned stimuli influence instrumental learning and its neural mechanisms.

Despite substantial differences between Pavlovian and instrumental learning, numerous studies show that Pavlovian conditioned stimuli can directly influence instrumental conditioning under many circumstances [?, ?]. For example, presenting appetite-inducing conditioned stimuli promotes lever-pressing for food [?, ?, ?, ?, ?, ?, ?]. Similarly, presenting alcohol-related cue stimuli elicits instrumental behavior for alcohol rewards in alcohol-addicted individuals [?, ?]. Since Pavlovian conditioned stimuli can facilitate instrumental learning, they may also cause the transition from goal-directed to habitual learning. Evidence supporting this inference comes from animal models showing that stressors as unconditioned stimuli (e.g., foot shocks or predator odors) induce habitual behavioral shifts [?, ?].

Thus, we can understand that stress first affects individuals' Pavlovian learning as a conditioned or unconditioned stimulus, which then facilitates instrumental learning through PIT, leading to the transition from goal-directed to habitual learning.

5. Neural Mechanisms of Stress Effects on Dual-Learning Systems

Researchers have used fMRI and pharmacological manipulations (including receptor agonists and antagonists) to investigate the neural mechanisms through which stress influences dual-learning systems, yielding relatively clear conclusions. Key hormones in stress-induced habitual shifts include noradrenaline and glucocorticoids, with MR receptors as relevant targets, and critical brain regions including the amygdala as well as the previously mentioned hippocampus and dorsal striatum.

5.1 Hippocampus, Dorsal Striatum, and Amygdala

fMRI studies have found that stressed individuals tending toward habitual learning in probabilistic classification tasks show reduced hippocampal neural activity, a key region for cognitive control [?, ?, ?]. To explore how stress affects activation of habitual system brain regions, a recent study combining EEG and fMRI found significantly enhanced dorsal striatum activation in stressed participants [?, ?, ?, ?, ?, ?]. Other research from a functional connectivity perspective has revealed the amygdala’ s crucial role in stress-induced habitual responding. Specifically, these studies demonstrate that stress enhances amygdala-dorsal striatum functional connectivity while reducing amygdala-hippocampus connectivity [?, ?, ?, ?, ?]. Earlier rodent studies using the plus-maze task found that amygdala injections of yohimbine (an anxiogenic drug) caused rats to shift toward caudate nucleus-dependent (part of dorsal striatum) habitual learning [?, ?].

5.2 Noradrenaline

Notably, the anxiogenic properties of yohimbine in Packard’ s pharmacological manipulation study are partly attributable to its effects on the noradrenergic system, suggesting a role for noradrenaline in stress-induced habitual learning. To verify this, Wirz et al. (2017) examined probabilistic classification learning under stress in individuals with specific genetic differences, finding that carriers of the ADRA2B deletion variant showed reduced habitual biases compared to non-carriers under stress. The ADRA2B gene encodes the 2b-adrenoceptor in humans, and individuals lacking this gene cannot encode functional 2b-adrenoceptors, thereby blocking adrenergic hormone effects on the amygdala and reducing habitual responding. This study demonstrates that normal noradrenaline function constitutes an essential component.

5.3 Glucocorticoids and MR Receptors

Glucocorticoids such as human cortisol are considered primary modulators between stress and learning. To investigate glucocorticoid effects, researchers combined pharmacological manipulation with fMRI, administering MR receptor antagonists to experimental groups and revealing interactive effects of stress and MR receptors on amygdala-dorsal striatum functional connectivity [?, ?]. Schwabe et al. (2010) injected glucocorticoids into rats’dorsolateral and dorsomedial striatum before spatial maze tasks, finding that only dorsolateral striatum injections produced stimulus-response learning tendencies similar to overtrained rats. This study first established that the rat dorsolateral striatum constitutes the neural basis of habitual learning, with the human homolog being the putamen. Second, it demonstrated glucocorticoid effects and showed that pharmacological blockade could prevent stress-induced habitual biases in rats. Two additional human studies have replicated these glucocorticoid and MR receptor effects [?, ?, ?].

5.4 Interaction Between Noradrenaline and Glucocorticoids

The aforementioned studies demonstrate individual roles of noradrenaline and glucocorticoids in stress-induced habitual learning but do not directly reveal their interactive relationship in controlling behavior. To examine their interaction, researchers conducted pharmacological manipulation studies in which participants received either hydrocortisone alone, yohimbine alone, both drugs simultaneously, or no drug (control), before performing the outcome devaluation task [?, ?, ?, ?, ?]. Results showed that only participants who received both drugs exhibited outcome devaluation insensitivity during the test phase—indicating habitual responding—while those receiving either drug alone or placebo showed intact goal-directed behavior. Subsequently, researchers added fMRI to this design, replicating behavioral results while discovering that the noradrenaline-glucocorticoid interaction effect was significantly associated with reduced activity in the medial prefrontal cortex (mPFC) and orbitofrontal cortex [?, ?, ?, ?, ?]—brain regions that constitute the neural basis of goal-directed learning [?, ?]. Thus, the synergistic action of noradrenaline and glucocorticoids also damages the goal-directed learning system.

In summary, noradrenaline and glucocorticoids, under amygdala involvement, synergistically act on brain regions related to dual-learning systems—including the hippocampus, dorsal striatum, medial prefrontal cortex, and orbitofrontal cortex—thereby impairing spatial or goal-directed learning and causing the shift from reflective to reflexive system control.

6. Implications for Drug Addiction

Drug addiction is a chronic relapsing disorder characterized by compulsive drug seeking and impaired social functioning, imposing severe burdens on individuals, families, and society. Multiple factors including genetics, personality, social environment, and life events can contribute to addiction [?, ?, ?, ?, ?, ?], while research indicates that stress influences drug motivation, reward systems, and drug efficacy, playing a critical role in addiction development and relapse [?, ?, ?, ?]. The stress effects on dual-learning systems discussed herein enhance understanding of addiction formation and relapse, offering insights for clinical diagnosis and treatment [?, ?, ?].

Schwabe et al. (2011) proposed a cognitive model of stress effects on drug addiction, revealing the cognitive mechanisms underlying the progression from voluntary drug use to compulsive consumption and eventual relapse. Researchers suggest that during initial drug exposure, individuals are primarily controlled by the goal-directed system, but stress-induced executive function impairment prevents effective inhibition of drug intake. Following drug consumption, acute and chronic stress disrupt the balance between goal-directed and habitual systems' control over instrumental behavior, biasing individuals toward automated responses and resulting in increased drug seeking and intake, thereby establishing addiction. During withdrawal, the synergistic action of noradrenaline and glucocorticoids causes habitual system control over behavior. Since stimulus-response associations have already formed, drug-related cue stimuli can trigger drug seeking and intake responses, increasing relapse risk. Additional studies by these researchers found that beta-blockers or glucocorticoid antagonists may help prevent addiction relapse [?, ?, ?, ?, ?]. In summary, stress effects on drug addiction and relapse are mediated by elevated cortisol levels and promoted dual-learning system imbalance.

Stress effects on drug addiction can also be understood through the psychological mechanism of Pavlovian-Instrumental Transfer. Pavlovian conditioned stimuli facilitate instrumental learning, causing the transition from goal-directed to habitual learning. Additionally, research shows that individuals with early-life stress have larger amygdalae and stronger fear conditioning [?, ?]. It can thus be inferred that aversive Pavlovian fear cues also produce this effect, particularly in individuals with amygdala dysfunction, where habitual tendencies become more pronounced. Therefore, aversive conditioned stimuli can alter individuals' instrumental behavior, and when individuals with early-life stress histories recall past aversive events for any reason, they are more likely to exhibit habitual behavior and consequently face greater risks for substance abuse and drug addiction [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?].

These two models demonstrate that stress plays a critical role in addiction formation and relapse by affecting hormone levels or brain structures, thereby causing dual-learning system imbalance. Therefore, clinical interventions for drug addiction could target the stress component, such as administering drugs that block cortisol-MR receptor binding or using cognitive training to enhance stress coping abilities, thereby indirectly and effectively controlling addiction progression.

7. Summary and Outlook

In summary, we have reviewed the cognitive processes and physiological mechanisms underlying dual-learning system imbalance under acute or chronic stress, and reinterpreted drug addiction formation and relapse from this perspective. In emergency or uncontrollable situations, acute stress responses can temporarily enhance alertness and attention, prompting individuals to employ habitual systems for faster behavioral responses while conserving cognitive resources—considered an adaptive mechanism [?, ?]. However, when stressors subside, failure to reverse these stress-induced habitual responses severely impairs learning flexibility and memory accuracy [?, ?]. Moreover, prolonged stress experiences and maladaptive habitual behaviors can lead to stress-related psychological and psychiatric disorders such as post-traumatic stress disorder and drug addiction [?, ?, ?, ?, ?, ?, ?]. Indeed, the shift toward habitual learning under stress can be adaptive in the short term, but sustained imbalance in learning systems negatively impacts individuals.

Currently, substantial research has accumulated on dual-learning systems under stress. However, we believe future research should address the following issues:

First, regarding the definition of habitual systems and the reliability of experimental tasks. Many studies employ different tasks and generally define habitual learning as inflexible, automatic behavior based on stimulus-response associations. However, the specific features and attributes of habitual learning in each task remain unclear—for instance, whether habitual behavior is innate or gradually acquired, and whether it requires attention or conscious awareness. Even with identical paradigms, neuroimaging studies report varying activation patterns. A recent meta-analysis of human habitual learning found that probabilistic classification learning studies reported caudate nucleus activation, some reporting both caudate and putamen activation with voxel peaks in anterior regions. Conversely, maze navigation studies mostly found caudate activation with posterior voxel peaks. Notably, this meta-analysis also found that outcome devaluation and reinforcement learning paradigms yielded more consistent results, commonly reporting lateral putamen activation [?, ?]. The human putamen, like the rodent dorsal striatum, constitutes a primary brain region for habitual behavior. These results suggest that outcome devaluation and reinforcement learning tasks more effectively dissociate habitual from goal-directed systems compared to navigation and probabilistic classification tasks, representing more reliable paradigms for studying human habitual behavior. Future research could combine these latter paradigms with earlier ones to directly confirm habitual responding and more effectively identify individuals or populations insensitive to devaluation.

Second, regarding individual differences in the relationship between stress and dual-learning systems. Stress is fundamentally a subjective experience of the external environment, and this subjectivity creates population heterogeneity—a situation that is stressful for one person may be motivating for another. Additionally, as previously discussed, individual differences in working memory capacity or IQ influence stress responses. Evidence suggests that some cognitive differences are genetically determined. For example, the ADRA2B gene encoding the 2b-adrenoceptor shows stronger amygdala activation in carriers under stress [?, ?], while Wirz et al. (2017) found that ADRA2B deletion variant carriers exhibited reduced habitual biases under stress in probabilistic classification learning. Future research could build on these findings to examine how individual differences, particularly at the genetic level, moderate stress effects on dual-learning systems, ultimately providing personalized treatment approaches for stress-sensitive populations in clinical applications.

Third, temporal factors of stressors require consideration. These include stress-task latency (time between stress induction and task), stressor duration, and early-life stress [?, ?, ?, ?, ?]. Stress-task latency refers to the interval between stress and task. Because GR and MR receptors have different affinities for glucocorticoids under HPA axis influence—MR receptors have higher affinity and rapidly induce neuronal excitation upon hormone binding, whereas GR receptors have lower affinity and cause slow network inhibition—correcting for stress-task latency is crucial for interpreting HPA axis-related results. Studies show that differences of just a few minutes can affect stress impacts on risk-taking behavior [?, ?, ?, ?, ?]. By duration, stress can be acute or chronic. Research in animals [?, ?] and humans [?, ?] shows that chronic stress (repeated stressor presentation) correlates with structural changes in decision-related brain regions more than acute stress does. Similarly, for early-life stress, effects on decision-making vary across the lifespan depending on stress experiences [**?**, **?**]. For example, adolescents experiencing early-life stress show altered emotion- or motivation-related neural circuits (e.g., amygdala, prefrontal cortex, striatum) involved in decision-making [**?**, **?**]. Whether stress effects on dual-learning systems vary with these temporal factors awaits further investigation.

Finally, future research should employ multiple methodological approaches. Dias-Ferreira et al. (2009) examined stress effects on goal-directed behavior in mice, finding that after 21 days of stress (including social threat, forced swimming, and restraint), experimental mice could not modify habitual lever-pressing responses during devaluation. The study also revealed atrophy in ventromedial prefrontal cortex (vmPFC) and dorsomedial striatum, with concurrent dorsal striatum hypertrophy, providing direct evidence for brain mechanisms underlying stress-induced behavioral changes. However, ethical constraints prevent similar lesion studies in humans. Researchers have therefore adopted non-invasive methods such as transcranial direct current stimulation (tDCS), finding that stimulating dorsolateral prefrontal cortex effectively prevents stress-induced working memory impairment, revealing its critical role in the stress-working memory relationship [**?**, **?**]. Inspired by this, future studies could employ similar non-invasive techniques combined with functional neuroimaging and brain lesion patient studies to further identify and dissociate brain structural and functional changes in dual-learning systems under stress. More pharmacological manipulation studies are also needed to clarify neuroendocrine mechanisms. For instance, while MR receptor roles are well-established, GR receptors remain understudied. Although one study first demonstrated GR receptor involvement in chronic stress effects on instrumental behavior [**?**, **?**], their role in acute stress effects on dual-system balance is unknown. Future research could fill this gap.

References

Balleine, B. W. (2001). Incentive processes in instrumental conditioning. In R. R. Mowrer & S. B. Klein (Eds.), *Handbook of contemporary learning theories* (pp. 307-366). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Balleine, B. W., & O' Doherty, J. P. (2010). Human and rodent homologies in action control: corticostriatal determinants of goal-directed and habitual action. *Neuropsychopharmacology, 35*(1), 48-69.

Bogdanov, M., & Schwabe, L. (2016). Transcranial stimulation of the dorsolateral prefrontal cortex prevents stress-induced working memory deficits. *Journal of Neuroscience, 36*(4), 1429-1437.

Braun, S., & Hauber, W. (2013). Acute stressor effects on goal-directed action in rats. *Neurobiology of Learning and Memory, 20*(12), 700-709.

Brewer, D. D., Catalano, R. F., Haggerty, K., Gainey, R. R., & Fleming, C. B. (1998). A meta-analysis of predictors of continued drug use during and after treatment for opiate addiction. *Addiction, 93*(1), 73-92.

Cousijn, H., Rijpkema, M., Qin, S., van Marle, H. J., Franke, B., Hermans, E. J., . . . Fernandez, G. (2010). Acute stress modulates genotype effects on amygdala processing in humans. *Proceedings of the National Academy of Sciences of the United States of America, 107*(21), 9867-9872.

Dandolo, L. C., & Schwabe, L. (2016). Stress-induced cortisol hampers memory generalization. *Neurobiology of Learning and Memory, 23*(12), 679-683.

Daw, N. D., Gershman, S. J., Seymour, B., Dayan, P., & Dolan, R. J. (2011). Model-based influences on humans' choices and striatal prediction errors. *Neuron, 69*(6), 1204-1215.

Daw, N. D., Niv, Y., & Dayan, P. (2005). Uncertainty-based competition between prefrontal and dorsolateral striatal systems for behavioral control. *Nature Neuroscience, 8*(12), 1704-1711.

de Quervain, D., Schwabe, L., & Roozendaal, B. (2017). Stress, glucocorticoids and memory: implications for treating fear-related disorders. *Nature Reviews Neuroscience, 18*(1), 7-19.

de Quervain, D. J., Roozendaal, B., & McGaugh, J. L. (1998). Stress and glucocorticoids impair retrieval of long-term spatial memory. *Nature, 394*(6695), 787-790.

Dias-Ferreira, E., Sousa, J. C., Melo, I., Morgado, P., Mesquita, A. R., Cerqueira, J. J., . . . Sousa, N. (2009). Chronic stress causes frontostriatal reorganization and affects decision-making. *Science, 325*(5940), 621-625.

Dickinson, A. (1985). Actions and habits: the development of behavioural autonomy. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 308*(1135), 67-78.

Dube, S. R., Felitti, V. J., Dong, M., Chapman, D. P., Giles, W. H., & Anda, R. F. (2003). Childhood abuse, neglect, and household dysfunction and the risk of illicit drug use: the adverse childhood experiences study. *Pediatrics, 111*(3), 564-572.

Dube, S. R., Felitti, V. J., Dong, M., Giles, W. H., & Anda, R. F. (2003). The impact of adverse childhood experiences on health problems: evidence from four birth cohorts dating back to 1900. *Preventive medicine, 37*(3), 268-277.

Foerde, K., Knowlton, B. J., & Poldrack, R. A. (2006). Modulation of competing memory systems by distraction. *Proceedings of the National Academy of Sciences of the United States of America, 103*(31), 11778-11783.

Fournier, M., d’ Arripe-Longueville, F., & Radel, R. (2017). Effects of psychosocial stress on the goal-directed and habit memory systems during learning and later execution. *Psychoneuroendocrinology, 77*, 275-283.

Gershman, S. J., Markman, A. B., & Otto, A. R. (2014). Retrospective revaluation in sequential decision making: a tale of two systems. *Journal of Experimental Psychology: General, 143*(1), 182-194.

Gilovich, T., Griffin, D., & Kahneman, D. (2002). *Heuristics and biases: The psychology of intuitive judgment.* Cambridge university press.

Glascher, J., Daw, N., Dayan, P., & O’ Doherty, J. P. (2010). States versus rewards: dissociable neural prediction error signals underlying model-based and model-free reinforcement learning. *Neuron, 66*(4), 585-595.

Goodman, J., Leong, K. C., & Packard, M. G. (2012). Emotional modulation of multiple memory systems: implications for the neurobiology of post-traumatic stress disorder. *Reviews in the Neurosciences, 23*(5-6), 627-643.

Gourley, S. L., Swanson, A. M., Jacobs, A. M., Howell, J. L., Mo, M., Dileone, R. J., . . . Taylor, J. R. (2012). Action control is mediated by prefrontal BDNF and glucocorticoid receptor binding. *Proceedings of the National Academy of Sciences of the United States of America, 109*(50), 20714-20719.

Hall, J., Parkinson, J. A., Connor, T. M., Dickinson, A., & Everitt, B. J. (2001). Involvement of the central nucleus of the amygdala and nucleus accumbens core in mediating Pavlovian influences on instrumental behaviour. *European Journal of Neuroscience, 13*(10), 1984-1992.

Ishizuka, K., Hillier, A., & Beversdorf, D. Q. (2007). Effect of the cold pressor test on memory and cognitive flexibility. *Neurocase, 13*(3), 154-157.

Juster, R.-P., McEwen, B. S., & Lupien, S. J. (2010). Allostatic load biomarkers of chronic stress and impact on health and cognition. *Neuroscience and Biobehavioral Reviews, 35*(1), 2-16.

Kim, J. J., Lee, H. J. J., Han, J. S., & Packard, M. G. (2001). Amygdala is critical for stress-induced modulation of hippocampal long-term potentiation and learning. *Journal of Neuroscience, 21*(14), 5222-5228.

Kirschbaum, C., Pirke, K. M., & Hellhammer, D. H. (1993). The Trier Social Stress Test - A Tool for Investigating Psychobiological Stress Responses in a Laboratory Setting. *Neuropsychobiology, 28*(1-2), 76-81.

Koolhaas, J. M., Bartolomucci, A., Buwalda, B., de Boer, S. F., Fluegge, G., Korte, S. M., . . . Fuchs, E. (2011). Stress revisited: A critical evaluation of the stress concept. *Neuroscience and Biobehavioral Reviews, 35*(5), 1291-1301.

Lupien, S. J., Gillin, C. J., & Hauger, R. L. (1999). Working memory is more sensitive than declarative memory to the acute effects of corticosteroids: A dose-response study in humans. *Behavioral Neuroscience, 113*(3), 420-430.

Lupien, S. J., McEwen, B. S., Gunnar, M. R., & Heim, C. (2009). Effects of stress throughout the lifespan on the brain, behaviour and cognition. *Nature Reviews Neuroscience, 10*(6), 434-445.

Macleod, J., Hickman, M., Jones, H. E., Copeland, L., McKenzie, J., De Angelis, D., . . . Robertson, J. R. (2013). Early life influences on the risk of injecting drug use: case control study based on the Edinburgh Addiction Cohort. *Addiction, 108*(4), 743-750.

McEwen, B. S. (2007). Physiology and neurobiology of stress and adaptation: central role of the brain. *Physiological Reviews, 87*(3), 873-904.

McEwen, B. S. (2008). Central effects of stress hormones in health and disease: Understanding the protective and damaging effects of stress and stress mediators. *European Journal of Pharmacology, 583*(2-3), 174-185.

Otto, A. R., Gershman, S. J., Markman, A. B., & Daw, N. D. (2013). The curse of planning: dissecting multiple reinforcement-learning systems by taxing the central executive. *Psychological Science, 24*(5), 751-761.

Otto, A. R., Raio, C. M., Chiang, A., Phelps, E. A., & Daw, N. D. (2013). Working-memory capacity protects model-based learning from stress. *Proceedings of the National Academy of Sciences of the United States of America, 110*(52), 20941-20946.

Pabst, S., Brand, M., & Wolf, O. T. (2013). Stress and decision making: A few minutes make all the difference. *Behavioural Brain Research, 250*, 39-45.

Packard, M. G. (2009). Anxiety, cognition, and habit: a multiple memory systems perspective. *Brain Research, 1293*, 121-128.

Packard, M. G., & Goodman, J. (2012). Emotional arousal and multiple memory systems in the mammalian brain. *Frontiers in Behavioral Neuroscience, 6*, 14.

Packard, M. G., & Knowlton, B. J. (2002). Learning and memory functions of the Basal Ganglia. *Annual Review of Neuroscience, 25*, 563-593.

Packard, M. G., & Wingard, J. C. (2004). Amygdala and "emotional"modulation of the relative use of multiple memory systems. *Neurobiology of Learning and Memory, 82*(3), 243-252.

Patterson, T. K., & Knowlton, B. J. (2018). Subregional specificity in human striatal habit learning: a meta-analytic review of the fMRI literature. *Current Opinion in Behavioral Sciences, 20*, 75-82.

Piazza, P. V., & Le Moal, M. (1998). The role of stress in drug self-administration. *Trends in Pharmacological Sciences, 19*(2), 67-74.

Poldrack, R. A., Clark, J., Pare-Blagoev, E. J., Shohamy, D., Creso Moyano, J., Myers, C., & Gluck, M. A. (2001). Interactive memory systems in the human brain. *Nature, 414*(6863), 546-550.

Qin, S., Hermans, E. J., van Marle, H. J., Luo, J., & Fernandez, G. (2009). Acute psychological stress reduces working memory-related activity in the dorsolateral prefrontal cortex. *Biological Psychiatry, 66*(1), 25-32.

Radenbach, C., Reiter, A. M., Engert, V., Sjoerds, Z., Villringer, A., Heinze, H. J., . . . Schlagenhauf, F. (2015). The interaction of acute and chronic stress impairs model-based behavioral control. *Psychoneuroendocrinology, 53*, 268-280.

Rescorla, R. A., & Solomon, R. L. (1967). Two-process learning theory: Relationships between Pavlovian conditioning and instrumental learning. *Psychological Review, 74*(3), 151-182.

Salvador, A., Worbe, Y., Delorme, C., Coricelli, G., Gaillard, R., Robbins, T. W., . . . Palminteri, S. (2017). Specific effect of a dopamine partial agonist on counterfactual learning: evidence from Gilles de la Tourette syndrome. *Scientific Reports, 7*(1), 6292.

Schneiderman, N., Ironson, G., & Siegel, S. D. (2005). Stress and health: Psychological, behavioral, and biological determinants. *Annual Review of Clinical Psychology (Vol. 1, pp. 607-628).*

Schoofs, D., Wolf, O. T., & Smeets, T. (2009). Cold pressor stress impairs performance on working memory tasks requiring executive functions in healthy young men. *Behavioral Neuroscience, 123*(5), 1066-1075.

Schwabe, L., Bohbot, V. D., & Wolf, O. T. (2012). Prenatal stress changes learning strategies in adulthood. *Hippocampus, 22*(11), 2136-2143.

Schwabe, L., Dalm, S., Schachinger, H., & Oitzl, M. S. (2008). Chronic stress modulates the use of spatial and stimulus-response learning strategies in mice and man. *Neurobiol Learn Mem, 90*(3), 495-503.

Schwabe, L., Dickinson, A., & Wolf, O. T. (2011). Stress, habits, and drug addiction: a psychoneuroendocrinological perspective. *Experimental and clinical psychopharmacology, 19*(1), 53-63.

Schwabe, L., Hoffken, O., Tegenthoff, M., & Wolf, O. T. (2011). Preventing the stress-induced shift from goal-directed to habit action with a beta-adrenergic antagonist. *Journal of Neuroscience, 31*(47), 17317-17325.

Schwabe, L., Oitzl, M. S., Philippsen, C., Richter, S., Bohringer, A., Wippich, W., & Schachinger, H. (2007). Stress modulates the use of spatial versus stimulus-response learning strategies in humans. *Neurobiology of Learning and Memory, 14*(1), 109-116.

Schwabe, L., Schächinger, H., de Kloet, E. R., & Oitzl, M. S. (2010). Corticosteroids operate as a switch between memory systems. *Journal of Cognitive Neuroscience, 22*(7), 1362-1372.

Schwabe, L., & Schachinger, H. (2018). Ten years of research with the Socially Evaluated Cold Pressor Test: Data from the past and guidelines for the future.

Psychoneuroendocrinology, 92, 155-161.

Schwabe, L., Tegenthoff, M., Hoffken, O., & Wolf, O. T. (2010). Concurrent glucocorticoid and noradrenergic activity shifts instrumental behavior from goal-directed to habitual control. *Journal of Neuroscience, 30*(24), 8190-8196.

Schwabe, L., Tegenthoff, M., Hoffken, O., & Wolf, O. T. (2012). Simultaneous glucocorticoid and noradrenergic activity disrupts the neural basis of goal-directed action in the human brain. *Journal of Neuroscience, 32*(30), 10146-10155.

Schwabe, L., Tegenthoff, M., Hoffken, O., & Wolf, O. T. (2013). Mineralocorticoid receptor blockade prevents stress-induced modulation of multiple memory systems in the human brain. *Biological Psychiatry, 74*(11), 801-809.

Schwabe, L., & Wolf, O. T. (2009). Stress prompts habit behavior in humans. *Journal of Neuroscience, 29*(22), 7191-7198.

Schwabe, L., & Wolf, O. T. (2010). Socially evaluated cold pressor stress after instrumental learning favors habits over goal-directed action. *Psychoneuroendocrinology, 35*(7), 977-986.

Schwabe, L., & Wolf, O. T. (2011). Stress-induced modulation of instrumental behavior: From goal-directed to habitual control of action. *Behavioural Brain Research, 219*(2), 321-328.

Schwabe, L., & Wolf, O. T. (2012). Stress modulates the engagement of multiple memory systems in classification learning. *Journal of Neuroscience, 32*(32), 11042-11049.

Seehagen, S., Schneider, S., Rudolph, J., Ernst, S., & Zmyj, N. (2015). Stress impairs cognitive flexibility in infants. *Proceedings of the National Academy of Sciences of the United States of America, 112*(41), 12882-12886.

Shohamy, D., Myers, C. E., Grossman, S., Sage, J., Gluck, M. A., & Poldrack, R. A. (2004). Cortico-striatal contributions to feedback-based learning: converging data from neuroimaging and neuropsychology. *Brain, 127*, 851-859.

Shohamy, D., Myers, C. E., Hopkins, R. O., Sage, J., & Gluck, M. A. (2009). Distinct hippocampal and basal ganglia contributions to probabilistic learning and reversal. *Journal of Cognitive Neuroscience, 21*(9), 1821-1833.

Sinha, R. (2001). How does stress increase risk of drug abuse and relapse? *Psychopharmacology, 158*(4), 343-359.

Sinha, R. (2008). Chronic stress, drug use, and vulnerability to addiction. *Annals of the new York Academy of Sciences, 1141*(1), 105-130.

Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological bulletin, 119*(1), 3-22.

Smeets, T., Cornelisse, S., Quaedflieg, C. W., Meyer, T., Jelicic, M., & Merckelbach, H. (2012). Introducing the Maastricht Acute Stress Test (MAST): a quick and non-invasive approach to elicit robust autonomic and glucocorticoid stress responses. *Psychoneuroendocrinology, 37*(12), 1998-2008.

Soares, J. M., Sampaio, A., Ferreira, L. M., Santos, N., Marques, F., Palha, J. A., . . . Sousa, N. (2012). Stress-induced changes in human decision-making are reversible. *Translational psychiatry, 2*(7), e131.

Sutton, R. S., & Barto, A. G. (1998). *Reinforcement learning: An introduction* (Vol. 1): MIT press Cambridge.

Tolman, E. C., Ritchie, B. F., & Kalish, D. (1946). Studies in spatial learning. II. Place learning versus response learning. *Journal of experimental psychology, 36*(3), 221-229.

Tottenham, N., & Galvan, A. (2016). Stress and the adolescent brain: Amygdala-prefrontal cortex circuitry and ventral striatum as developmental targets. *Neuroscience and Biobehavioral Reviews, 70*, 217-227.

Tottenham, N., & Sheridan, M. A. (2010). A review of adversity, the amygdala and the hippocampus: a consideration of developmental timing. *Frontiers in Human Neuroscience, 3*, 68.

Trapp, S., O' Doherty, J. P., & Schwabe, L. (2018). Stressful Events as Teaching Signals for the Brain. *Trends in Cognitive Sciences, 22*(6), 475-478.

Ulrich-Lai, Y. M., & Herman, J. P. (2009). Neural regulation of endocrine and autonomic stress responses. *Nature Reviews Neuroscience, 10*(6), 397-409.

Valentin, V. V., Dickinson, A., & O' Doherty, J. P. (2007). Determining the neural substrates of goal-directed learning in the human brain. *Journal of Neuroscience, 27*(15), 4019-4026.

van Bakel, H. J., & Riksen-Walraven, J. M. (2004). Stress reactivity in 15-month-old infants: links with infant temperament, cognitive competence, and attachment security. *Developmental Psychobiology, 44*(3), 157-170.

Vogel, S., Fernandez, G., Joels, M., & Schwabe, L. (2016). Cognitive Adaptation under Stress: A Case for the Mineralocorticoid Receptor. *Trends in Cognitive Sciences, 20*(3), 192-203.

Vogel, S., Klumpers, F., Krugers, H. J., Fang, Z., Oplaat, K. T., Oitzl, M. S., . . . Fernandez, G. (2015). Blocking the mineralocorticoid receptor in humans prevents the stress-induced enhancement of centromedial amygdala connectivity with the dorsal striatum. *Neuropsychopharmacology, 40*(4), 947-956.

Vogel, S., Klumpers, F., Schroder, T. N., Oplaat, K. T., Krugers, H. J., Oitzl, M. S., . . . Fernandez, G. (2017). Stress induces a shift towards striatum-dependent stimulus-response learning via the mineralocorticoid receptor. *Neuropsychopharmacology, 42*(6), 1262-1271.

von Dawans, B., Kirschbaum, C., & Heinrichs, M. (2011). The Trier Social Stress Test for Groups (TSST-G): A new research tool for controlled simultaneous social stress exposure in a group format. *Psychoneuroendocrinology, 36*(4), 514-522.

Wirz, L., Wacker, J., Felten, A., Reuter, M., & Schwabe, L. (2017). A deletion variant of the 2b-adrenoceptor modulates the stress-induced shift from "cognitive" to "habit" memory. *Journal of Neuroscience, 37*(8), 2180-2186.

Yin, H. H., & Knowlton, B. J. (2006). The role of the basal ganglia in habit formation. *Nature Reviews Neuroscience, 7*(6), 464-476.