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Review

Stress-induced modulation of instrumental behavior: From goal-directed to habitual control of action

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ABSTRACT

Actions that are directed at achieving pleasant or avoiding unpleasant states are referred to as instrumental. The acquisition of instrumental actions can be controlled by two anatomically and functionally distinct processes: a goal-directed process that is based on the prefrontal cortex and dorsomedial striatum and encodes the causal relationship between an action and the motivational value of the outcome and a dorsolateral striatum-based habit process that learns associations between actions and antecedent stimuli. Here, we review recent research showing that stress modulates the control of instrumental action in a manner that favors habitual over goal-directed action. At the neuroendocrine level, this stress-induced shift towards habit action requires the concerted action of glucocorticoids and noradrenergic arousal and is most likely accompanied by opposite functional changes in the corticostriatal circuits underlying goal-directed and habitual actions. Although generally adaptive, these changes in the control of instrumental action under stress may promote dysfunctional behaviors and the development of psychiatric disorders such as addiction.

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1. Introduction

Well established behaviors are difficult to change. For example, most people from mainland Europe, who are used to right-hand traffic, have difficulties to adjust to driving on the left side of the road in countries like the United Kingdom or Australia. One explanation for the relative resistance of frequently repeated behavior to change is that, with practice, behaviors become more and more automatic and less explicit. This shift from explicit to implicit

control of behavior, the so-called proceduralization, is considered an indicator of successful learning [1] because it sets cognitive resources free for other tasks. In the example of driving, experienced drivers can steer, brake, and change the gear automatically, while holding a conversation or tuning the radio. However, the proceduralization of behavior comes with a price in terms of flexibility and cognitive control, frequently reducing the capacity to respond quickly to changes in the environment (e.g. children running into the street).

Contemporary instrumental learning theory describes the automaticity of behavior after extended practice as a consequence of a transition from goal-directed to habitual control of action [2]. Initially, control of behavior is largely goal-directed but with repeated practice there is a gradual shift to habitual control [3]. Recent

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research indicates that, in addition to extended practice, also emotional factors may promote the shift from goal-directed to habitual action [4,5].

In the present review, we will focus on the influence of stressful episodes on the control of instrumental behavior. Instrumental learning refers to learning how to act to achieve a desired state and there is compelling evidence that it can be controlled by two processes operating in tandem: a flexible goal-directed process that encodes the relationship between action and outcome and a rather rigid habit process that builds associations between responses and preceding stimuli without any link to the outcome that the response engendered [2,6]. In the first part of this review, we will portray these two processes and their neural underpinnings. Then, we will review recent studies showing that stress, whether acute or chronic, may facilitate habitual over goal-directed instrumental action. Finally, we will discuss potential implications of the stress-induced modulation of instrumental behavior for psychopathology.

2. Instrumental learning: goal-directed and habit processes

Classical theories on instrumental behavior emphasized the association between stimuli and responses [7]. They claimed that the presentation of a reward after a certain response would strengthen the association between stimuli that were present when the response was performed and the response itself, thus enabling the stimuli to trigger the response. Although such stimulus–response (S–R) theories are still popular [8] and there is little doubt that some of our actions are based on an S–R mechanism (e.g. stopping your car at a red light), classical S–R theories face two problems [2]. First, it has become clear that instrumental behavior is rather determined by the contingency (or causal relationship) between action and outcome than by the mere contiguity between them, as proposed by earlier S–R theories [9–11]. Second, according to the S–R view instrumental behavior should be largely unaffected by the individuals' current needs and motivational status, which is contrary to both our folk psychology and a large body of empirical evidence [12–14].

More recent theories of instrumental behavior postulate that instrumental action may be mediated by at least three different learning processes [2,15,16]: (i) a contingency learning process that encodes the (causal) relationship between an action and an outcome; (ii) an incentive learning process during which an instrumental value is assigned to the outcome, depending on the individuals' current motivational state; and (iii) the classical S–R learning process. While the former two processes allow for purposive, goal-directed instrumental action, the latter mediates rigid, habitual instrumental responding.

2.1. Separating goal-directed and habitual actions

Goal-directed and habitual processes work often in concert and the same action may be controlled by goal-directed or habitual processes. To separate goal-directed and habitual actions in the lab, two sophisticated behavioral assays were developed that are based on the idea that goal-directed but not habitual action is sensitive to changes in the motivational value of the outcome and the action–outcome contingency: outcome devaluation and contingency degradation.

In a typical devaluation experiment [12,14,17,18], subjects are first trained in two instrumental actions that are followed by distinct food rewards. After training, one of the food rewards is devalued by feeding subjects to satiety with that food or by taste aversion learning; the instrumental value of the other outcome remains intact. The effect of the selective food devaluation is then assessed in an extinction test in which the rewards are not pre-

sented any longer. If the subject decreases responding to the action that had previously been associated with the now devalued outcome, its behavior is considered goal-directed. Alternatively, if the subject continues to perform the devalued action, i.e., is insensitive to the change in the value of the outcome, its behavior is interpreted as habitual.

In contingency degradation tests, free rewards are introduced that are independent of any action [19,20]. Again, subjects are first trained in two instrumental actions leading to two distinct outcomes. In the critical test session, one of the outcomes is presented non-contiguously, i.e., unpaired with the action, such that its probability is equally likely if the previously required action is shown or not. As we have mentioned above, goal-directed but not habitual (S–R) processes are assumed to be sensitive to the contingency between action and outcome. Consequently, a decrease in responding to the action associated with the non-contiguously presented reward indicates goal-directed action, whereas its absence indicates habit behavior.

These tests clearly indicated that humans and rodents are capable of both goal-directed and habit-based actions [13,14,18,19]. Which process controls behavior seems to depend critically on the amount of training. Initially, behavior is mostly goal-directed, i.e., sensitive to outcome devaluation or contingency degradation. After extensive training (overtraining), however, it loses its sensitivity to changes in goal value and action–outcome contingency and rather reflexive habit behavior predominates [13,21,22]. For example, rats that were trained to lever press for a total of 120 food pellets decreased lever pressing after they were given free access to food. Rats that were trained to lever press for a total of 360 food pellets, however, were insensitive to the devaluation of the food [13]. Similarly, human subjects who were trained to press different buttons to get different snack foods were sensitive to the devaluation of the snack food if they had received a moderate amount of instrumental training but not if they were overtrained [18].

Another factor that affects the contribution of goal-directed and habitual processes to instrumental action is the reinforcement schedule used during training [6,23]. Ratio schedules, in which a response is followed with a certain probability by a reward, promote goal-directed action because the experienced correlation between action and outcome is high in these schedules. Interval schedules, in which a response is rewarded only after a certain time interval has elapsed, however, facilitate habitual responding because in these schedules the experienced instrumental contingency is usually low. The finding that even limited training on an interval schedule may render behavior habitual [24] suggests that habit formation is not necessarily a consequence of practice per se. Overtraining may reduce the variation in behavior and thus the experienced correlation between action and outcome. If this action–outcome knowledge is absent (or reduced), it is not surprising that behavior is no longer sensitive to variations in the value of the outcome or the instrumental contingency [6].

2.2. Neural substrates of goal-directed and habit actions

The reported differences between goal-directed and habitual actions strongly suggest that these modes of instrumental action are dependent on different neural networks in the brain. Support for this idea comes from recent studies in rodents and humans.

Lesion studies in rats implicated the prelimbic prefrontal cortex and the part of the dorsal striatum that receives input from this cortical area, the dorsomedial striatum, in goal-directed action. Inactivations of these regions rendered instrumental action even after minimal training insensitive to outcome devaluation or con-

tingency degradation and thus habitual [2,19,25]. Interestingly, however, the prelimbic prefrontal cortex and the dorsomedial striatum seem to play different roles in the acquisition and expression of goal-directed behavior. Although lesions of the prelimbic prefrontal cortex impaired goal-directed action if they were performed before training, they had no effect if they were performed after initial training [26], indicating that this region is relevant for the acquisition but not for the expression of goal-directed behavior. Lesions of the dorsomedial striatum, however, disrupted goal-directed behavior irrespective of the time point of the lesion [19], thus suggesting that this area is involved in both the acquisition and expression of goal-directed behavior. Another part of the dorsal striatum, the dorsolateral striatum, plays a key role in habit behavior. Rats with lesions of the dorsolateral striatum remained after extensive training, that led to habitual responding in sham-operated rats, sensitive to changes in outcome value and action–outcome contingency, i.e., they behaved even after overtraining goal-directed [27,28].

Recent fMRI studies in humans aimed to identify the neural substrates of goal-directed and habit learning in the human brain (for an excellent review on this topic see [29]). In a first fMRI study that used a formal test of goal-directed vs. habit action, participants were trained in two instrumental actions before one of these actions was devalued by feeding participants to satiety on the respective food [14]. In the following extinction test, goal-directed behavior (i.e., the decrease in the choice of the devalued action) correlated significantly with the activity of the (medial and lateral) orbitofrontal cortex. In line with these findings, another study in which the contingency between action and outcome was varied across instrumental training showed that activity in the medial orbitofrontal cortex was modulated as a function of action–outcome contingency [30]. In addition, contingency related changes were found in the activity of the anterior caudate nucleus, the human homologue of the dorsomedial striatum in rats. Since the detection of action–outcome contingencies is a hallmark of goal-directed behavior, these findings suggest that the orbitofrontal cortex and the anterior caudate nucleus mediate goal-directed action in the human brain.

In a first test of the neural correlates of human habit behavior, participants' sensitivity to outcome devaluation was assessed either after moderate or extensive instrumental training [18]. As expected, participants were less sensitive to the decrease in outcome value after extensive training, which indicates that their behavior was habitual. Interestingly, the posterior putamen, which corresponds to the dorsolateral striatum in rats, showed a significant increase in activity to stimuli that were associated with a certain response as learning proceeded suggesting that this region mediates habit formation in humans.

In summary, there is by now a consensus that instrumental action is not controlled by a single S–R process but that it may be under the control of two anatomically and functionally distinct processes (see Table 1). Goal-directed processes learn the causal relationship between a certain action and the incentive value of a reward, whereas habitual S–R processes form associations between responses and antecedent stimuli. Lesion studies in rodents and human fMRI studies showed that these processes are subserved by different neural networks. In rats, goal-directed action is mediated by the prelimbic prefrontal cortex and the dorsomedial striatum, whereas habit action is mediated by the dorsolateral striatum (for a more comprehensive review of the neural correlates of goal-directed and habitual actions see [23,31]). The functional homologues of these structures in humans are the orbitofrontal cortex, the anterior caudate nucleus, and the posterior putamen, respectively. Since goal-directed and habitual processes may contribute to an action at the same time [31], one of the most interesting questions is which factors determine which of

Table 1
Key characteristics of goal-directed and habitual instrumental actions.

	Goal-directed action	Habit action
Cognitive demands	High	Low
Behavioral flexibility	High	Low
Sensitivity to changes	Sensitive to changes in the action–outcome contingency and the motivational value of the outcome	Stimulus-bound; insensitive to changes in action–outcome contingency or value of the outcome
Neural substrates	Dorsomedial striatum/anterior caudate nucleus Prelimbic prefrontal cortex/orbitofrontal cortex	Dorsolateral striatum/posterior putamen

the process dominates behavior. Until recently, the focus was on training-related factors such as the amount of training or the reinforcement schedule. Little was known about other situational or individual factors that might influence the control of instrumental behavior. During the past few years, however, evidence has accumulated that emotional factors can modulate instrumental action. In the following, we will review recent studies demonstrating that stress may promote a shift from goal-directed to habitual control of action.

3. Stress-induced modulation of instrumental action

It is well known that stress may influence cognitive functions, in particular learning and memory processes [32–35]. These effects are mainly mediated by neurotransmitters and hormones, such as glucocorticoids (cortisol in humans) and catecholamines, which are released in response to stressful experiences. One of the brain regions with the highest density of stress hormone receptors is the prefrontal cortex [36], suggesting that this area is particularly sensitive to stress and stress hormones. Indeed, there is evidence that stress disrupts synaptic plasticity processes in the prefrontal cortex [37]. Moreover, cognitive control processes that are supported by the prefrontal cortex [38] are impaired by stress [39,40]. By contrast, striatum-dependent S–R memory processes may be facilitated by stress and glucocorticoid stress hormones [41–43]. Based on these findings, it appears tempting to hypothesize that stress may modulate prefrontal cortex-based goal-directed and dorsolateral striatum-based habit processes in a way that biases instrumental action towards habit.

In a first test of this hypothesis, we exposed participants to the Socially Evaluated Cold Pressor Test [44], a stress protocol that combines physical and psychosocial stressors, or a non-stressful control condition before they learned two instrumental actions leading to two distinct food outcomes ([4]; see Fig. 1). In a selective outcome devaluation procedure, participants were invited to eat one of the foods to satiety, so that its incentive value was reduced. Participants' choice behavior in the following extinction test revealed a significant influence of stress on instrumental behavior (Fig. 2A). While control participants chose the action associated with the now devalued food outcome after the devaluation significantly less often than at the end of the learning session, stressed participants were insensitive to the change in the value of the outcome, they did not decrease their responding to the devalued action. In other words: stress before learning shifted instrumental action from goal-directed to habitual control. Remarkably, the behavioral insensitivity to the selective outcome devaluation after stress

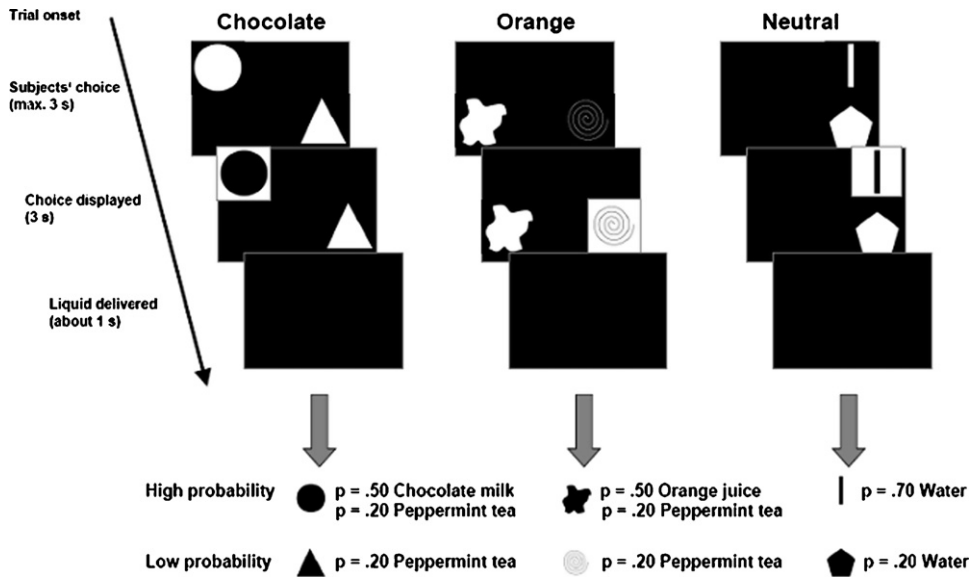


Fig. 1. Instrumental learning task that was used to separate goal-directed and habitual actions in humans. Participants completed three trial types (chocolate, orange, neutral). On each trial, they were asked to choose between two actions represented by unique symbols. In each trial type there was one action that led with a high probability to a food outcome and one action that led with a low probability to a food outcome. Depending on the trial type, the high probability action delivered chocolate milk and orange juice, respectively, with a probability of $p = .50$, a common liquid (peppermint tea) with a probability of $p = .20$ or else nothing. The high probability action yielded the common outcome with a probability of $p = .20$. After training, one of the rewards (orange juice or chocolate milk) was devalued by inviting subjects to eat that food to satiety. The behavioral sensitivity to this outcome devaluation in a following extinction test revealed whether behavior was goal-directed or habitual. The figure is reproduced from [4] with permission of the Society for Neuroscience.

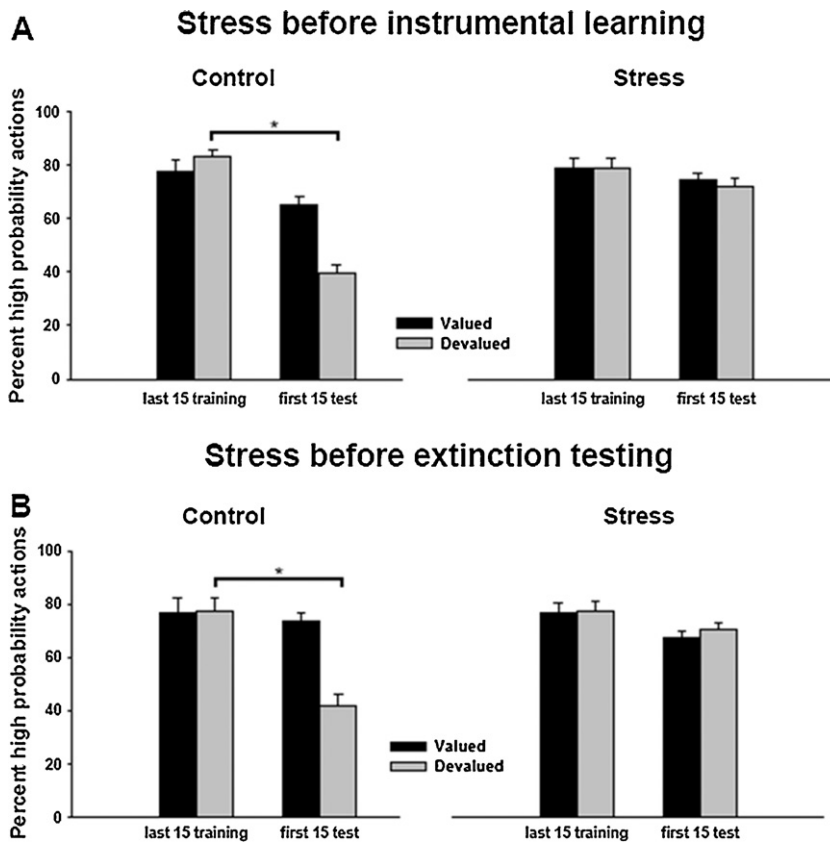


Fig. 2. Effect of stress before learning (A) or before extinction testing (B) on instrumental behavior. Participants were trained in two instrumental actions. One of the actions was devalued after training, while the value of the other action remained intact. Performance in an extinction test revealed whether behavior was goal-directed or habitual: goal-directed behavior was indicated by a decrease in responding to the devalued action from the last training trials to the first extinction test trials, habit behavior by the absence of such a decrease. Stress rendered participants' behavior habitual, irrespective of whether it was induced before learning or before extinction testing. Part A is reproduced from [4] with permission of the Society for Neuroscience; part B is reproduced from [47] with permission from Elsevier. * $p < .05$.

was paralleled by a reduction in explicit action–outcome knowledge. This finding underlines the habitual character of instrumental action after acute stress.

Shortly after this first demonstration of a stress effect on the control of instrumental action in humans, a similar effect was reported after chronic stress in rats [45]. Rats were repeatedly exposed to different stressors over 21 days. A few days after the last stress exposure, they were trained to press a lever to receive either food pellets or sucrose. Devaluation and contingency degradation tests were used to assess the goal-directed vs. habitual control of instrumental action. These tests showed that chronically stressed rats were insensitive to changes in outcome value and action–outcome contingency, indicating that their behavior was under habitual control. Thus, stress, whether acute or chronic, appears to favor habitual responding, at the expense of goal-directed instrumental action.

3.1. When does the shift occur?

These studies show that stress promotes a shift from goal-directed to habitual instrumental behavior. However, when does this shift occur? Does stress change already the acquisition of an action? Or, does it primarily affect the expression of an acquired action after its devaluation? The above cited studies cannot answer these questions because in both studies stress effects (e.g. elevated glucocorticoid levels) were present during training and extinction, thus making it impossible to separate effects on acquisition and expression of goal-directed and habit behavior. In order to disentangle stress effects on acquisition and expression of instrumental behavior, the interval between learning and extinction testing could be extended, so that the subjective and physiological stress mediators are at baseline level again at the time of extinction testing. This, however, is problematic because possible differences between the stress and control groups during extinction testing could be due to simple memory effects rather than to effects on the acquisition of instrumental behavior (in fact, stress effects on consolidation processes are well-known, see [46]). Alternatively, to isolate stress effects on the expression of instrumental behavior, stress may be induced before extinction testing, thereby ruling out any effects on acquisition.

We used this latter strategy in a recent study [47]. In this study, participants were again trained in two instrumental actions that were associated with different food outcomes and after training one of the two outcomes was devalued. This time, participants were exposed to the Socially Evaluated Cold Pressor Test before extinction testing. Similarly as in our previous study [4], stressed participants were insensitive to the change in the value of the outcome (see Fig. 2B). This finding shows that stress may render instrumental behavior habitual without any effects on learning.

One might be prone to take this finding as evidence that the previously observed effects of stress are mainly effects on the expression of instrumental behavior. This conclusion, however, might be premature because the effects of stress seem to be stronger if it is administered before instrumental learning than if it is administered before extinction testing. Participants who were stressed before learning performed the devalued action even after 45 extinction trials, whereas participants who were stressed after learning (and devaluation) performed the devalued action only in the first 15 trials of the extinction test. Furthermore, explicit action–outcome knowledge was impaired when stress was induced before learning but not when it was induced after learning. Indirect evidence for the view that stress may also affect the acquisition of instrumental actions comes from a recent study, in which several short extinction sessions were presented across instrumental learning [48]. Control participants were even after

120 trials sensitive to extinction, whereas stressed participants were already shortly after initial training insensitive to extinction. Although the resistance to extinction has no direct implications for goal-directed vs. habitual instrumental action, it can be speculated that the cause of the (pre-learning) stress-induced behavioral persistence is its habitual form [48]. In conclusion, the existing evidence suggests that stress may affect the expression of previously acquired actions without affecting processes involved in learning. If stress, however, may also influence the acquisition of instrumental actions (i.e., the actual formation of habits) remains still unknown.

3.2. How does stress change instrumental behavior?

The mechanism by which stress affects spatial or working memory processes is well documented: glucocorticoids and noradrenaline interact in the basolateral nucleus of the amygdala which then modulates memory processes in other brain areas such as the hippocampus or prefrontal cortex [33,49]. Eliminating any of these factors, for example by a glucocorticoid receptor antagonist, a beta blocker or lesions of the basolateral amygdala, prevents the stress effects on hippocampus- or prefrontal cortex-dependent memory [50–52]. Does stress affect the interplay of goal-directed and habitual processes via the same mechanism? How does stress change instrumental behavior?

Cortisol elevations in response to stress (before extinction testing) correlated significantly with participants' insensitivity to changes in the incentive value of the outcome [47], suggesting a role of glucocorticoids in the stress-induced modulation of instrumental action. The endocrinological mechanism underlying the effects of stress on instrumental behavior was directly addressed in a recent pharmacological study in which participants received either the synthetic glucocorticoid hydrocortisone, the alpha2-adrenergic receptor antagonist yohimbine, which increases noradrenergic activity, or a combination of both before they were tested in an outcome devaluation paradigm [53]. Same as placebo-treated controls, participants that had received hydrocortisone or yohimbine alone performed goal-directed; they chose the action that was associated with the devalued outcome significantly less often in the extinction test than at the end of the learning session (Fig. 3). The combined administration of hydrocortisone and yohimbine, however, rendered behavior habitual; participants that were administered both drugs were completely insensitive to the change in the value of the outcome. These findings suggest that glucocorticoids and noradrenergic arousal act also in concert to shift instrumental behavior from goal-directed to habitual control.

First insights into the neural mechanism via which stress modulates the control of instrumental action come from a recent rodent study [45]. Here, the (chronic) stress-induced bias towards habit behavior was accompanied by atrophy in the medial prefrontal cortex and dorsomedial striatum and by hypertrophy of the dorsolateral striatum, thus suggesting that (chronic) stress favors habits by causing opposite structural changes in the brain circuits supporting goal-directed and habitual actions. It appears rather unlikely that such structural changes occur after a single stress exposure and could thus account for the effects of acute stress on instrumental action. However, given that acute stress (hormone elevations) may reduce the activity of the prefrontal cortex in rodents and humans [37,54] and that S–R memory processes may be facilitated by acute stress [41,43], it seems possible that acute stress leads to opposite changes in the activity of the corticostriatal networks underlying goal-directed and habitual actions. Yet, in the absence of fMRI studies on the influence of acute stress on instrumental action, ideas about the brain mechanism

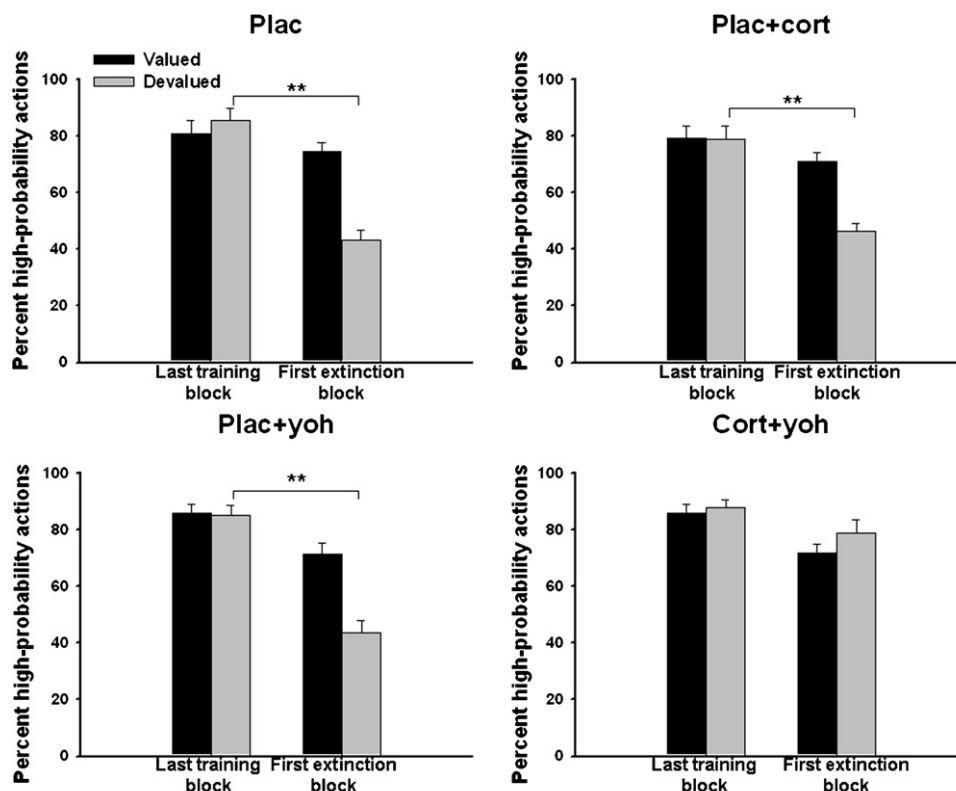


Fig. 3. Interactive influence of glucocorticoids and noradrenergic activity on instrumental action. Participants that received cortisol (cort) and the alpha-adrenergic antagonist yohimbine (yoh) before learning were insensitive to the change in the value of the action outcome, i.e., they performed habitual. Participants that received either cortisol or yohimbine performed goal-directed, same as participants that received a placebo (plac). Figure reproduced from [53] with permission of the Society for Neuroscience. $**p < .01$.

underlying the stress-induced shift towards habit action remain speculative.

4. Implications for psychopathology

Although habits are not necessarily bad and may help to organize our everyday lives efficiently [55], the aberrant recruitment of habit processes may have negative consequences and might promote even the development of psychiatric disorders such as addiction. In the terminology of instrumental learning theory, addictive behavior can be seen as the endpoint of a number of transitions from initially voluntary, goal-directed drug use to more and more involuntary, habitual and ultimately compulsory drug abuse [56–58]. Indeed, there is recent evidence that drug taking may become habitual if it is frequently repeated and that the transient inactivation of the dorsolateral striatum reinstates goal-directed drug use [59].

Interestingly, stress is a critical risk factor for the development of addiction as well as for relapse to addictive behavior after drug-free periods [60–62]. Based on the above reviewed studies showing that stress favors habitual action, we argued recently that acute stress may reinstate habitual responding to drug-related cues and thus increase the risk for relapse to drug abuse [63]. Furthermore, we have postulated that prolonged or repeated stress may accelerate the transition from voluntary to involuntary drug use and thereby promote the development of addictive behavior. This view might have important implications for the treatment of drug addiction. The finding that concurrent glucocorticoid and noradrenergic activity is required for the stress-induced shift towards habit action [53] points to a potential use of beta blockers or glucocorticoid receptor antagonists, particularly for the prevention of relapse. Moreover, existing psychotherapeutic approaches to the treatment of addic-

tion might be supplemented by elements that train goal-directed behavior and help patients to develop strategies to counteract established drug-related habits and routines.

In addition to their potential role in drug addiction, dysfunctional instrumental learning processes may also be involved in Parkinson's disease. It has recently been argued that the progressive loss of dopamine in the posterior putamen (the region that controls habitual action) that is a pathological hallmark of Parkinson's disease might force patients to rely on goal-directed processes of action control [64]. The difficulties that patients with Parkinson's disease have with normal automatic control of behavior might reflect deficits in habitual control processes which may in turn impede goal-directed actions. Although the effects of stress and stress hormones on instrumental action may be at least partly owing to stress-induced increases in dopaminergic activity, there is also evidence for a role of glucocorticoids and noradrenaline in the stress-induced shift towards habit action [53]. If glucocorticoids and noradrenaline could be used to facilitate habitual control processes in Parkinson's disease depends critically on whether the stress-induced changes in instrumental action are based on an enhancement of habit processes or on an impairment of goal-directed processes (or both) and is a challenge for future research.

5. Conclusions

Over the last decade, evidence has accumulated demonstrating that stress modulates the interaction of multiple memory systems (for a review see [35]). In particular, it has been repeatedly shown, in rodents and humans, that acute or chronic stress favors relatively simple S–R memory that is based on the striatum over cognitively more demanding spatial memory that is based on the medial temporal lobe [41,42,65–67]. Here, we have reviewed evi-

dence showing that stress may also modulate the use of different memory processes involved in instrumental action. Acute stress, either before or after instrumental learning, facilitates habitual action, at the expense of goal-directed action in humans [4,47]. Similarly, chronic stress biases instrumental behavior towards habits in rats [45]. These findings indicate that the modulatory effects of stress on multiple memory systems are not limited to spatial navigation tasks. Rather, they suggest that stress might generally favor simple but rigid memory processes over more elaborate but cognitively demanding memory processes. Stress seems to shift us from 'thinking' to 'doing'. This shift may help to reduce hesitations and delays in stressful situations and thus facilitate coping with the current stress. On the other hand, the aberrant engagement of habit processes under stress may impede the flexible adaptation to an ever-changing environment and might contribute in vulnerable phenotypes to the development of dysfunctional behaviors, such as drug addiction.

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