Feature Review

Leveraging cognitive neuroscience for making and breaking real-world habits

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Habits are the behavioral output of two brain systems. A stimulus–response (S–R) system that encourages us to efficiently repeat well-practiced actions in familiar settings, and a goal-directed system concerned with flexibility, prospection, and planning. Getting the balance between these systems right is crucial: an imbalance may leave people vulnerable to action slips, impulsive behaviors, and even compulsive behaviors. In this review we examine how recent advances in our understanding of these competing brain mechanisms can be harnessed to increase the control over both making and breaking habits. We discuss applications in everyday life, as well as validated and emergent interventions for clinical populations affected by the balance between these systems. As research in this area accelerates, we anticipate a rapid influx of new insights into intentional behavioral change and clinical interventions, including new opportunities for personalization of these interventions based on the neurobiology, environmental context, and personal preferences of an individual.

Habits and cognitive efficiency

Making that first cup of coffee in the morning, the route you take to work, and the order in which you prepare yourself for bed – habits play a central role in our lives. They are the behaviors that we perform reliably throughout the day when faced with familiar contexts and cues. A key characteristic of habits is their cognitive efficiency [1]. Someone relocating to a new city finds that each turn and intersection is at first a deliberate decision, but with every repetition these actions transition into near-automatic responses to environmental cues, rendering navigating second-nature where hardly a conscious thought is necessary to find the way to work. This transition is crucial because it frees up higher-order mental resources that can be reallocated for more complex tasks that demand attention [2]. In this way, the ability to form habits permits individuals to problem-solve, multi-task, and build simple behaviors into more complex repertoires. Because habits require fewer cognitive resources, they also serve as a fail-safe under suboptimal conditions, such as when feeling rushed, distracted, or stressed [3]. This is beneficial for behaviors that we might wish to perform with regularity, regardless of our current motivation, such as exercising or eating well.

The downside of habits is that our world is not static or perfectly predictable; when things change, the presence of well-trained habits can make it difficult to adapt. For example, driving on the opposite side of the street when abroad or getting used to a new password after changing it. Failing to adapt to these changes can manifest in action slips (e.g., taking a wrong turn or entering an old password) [4]. Moreover, research suggests that the same habit mechanisms may play a role in behaviors of clinical significance such as compulsions in obsessive-compulsive disorder (OCD) and addiction [5–9]. Given the ubiquity of habits and habit-like behaviors in everyday life, it is no surprise that the underlying mechanisms have been of considerable interest to basic researchers for decades [10,11]. In parallel,

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these have also interested applied researchers, not only with the aim of promoting 'good habits' that serve high-level goals but also to learn how to curb 'bad habits' in real-world settings [12,13]. Indeed, habits may be the most effective targets for behavioral change at the individual level [14].

In this review we draw on evidence from both basic science and applied research, aiming to provide a new playbook for how the rapidly advancing basic science of habits can be used to promote real-world behaviors that we wish to perform with regularity, and likewise to curb ingrained behaviors that have grown to be maladaptive. We define habits as behaviors triggered by contextual stimuli, developed through frequent repetition, that often persist regardless of current beliefs and goals. Crucially, we apply what is known as a 'dual system' perspective on the mental mechanisms that underpin habit expression. This dual system account conceptualizes habits as resulting from learned S–R associations, which can be modulated by **goal-directed control** (see Glossary) (based on currently held beliefs and goals) when sufficient attention and cognitive resources are available [15,16]. Some researchers refer to S–R associations as habit [17]. However, we reserve the term 'habit' for the observable behavior only, to more clearly delineate the multiple cognitive processes that contribute to whether or not a habit is expressed [18]. Importantly, from a dual system perspective, as we describe in detail in this review, modifying S–R associations is not the only pathway to promote or curtail the expression of habits.

The **dual system framework** has inspired a large body of research and has significantly advanced our understanding of habits, but recent critiques highlight the need for further exploration of alternative mechanisms [18–22]. Although the experimental evidence is consistent in some areas, it is mixed in others [23–26]. We explore the theoretical and methodological reasons behind these inconsistencies and provide insights into future research directions. We focus principally on research in humans ([27,28] for recent reviews in animals), but where appropriate we supplement this with insights derived from complementary methods applied across species. We cover research both in healthy participants and everyday habits ([16,17,29] for recent related reviews), as well as clinical populations where maladaptive habit expression has been implicated, drawing on what we know about their phenomenology, neurobiology, and treatment to further inform habit-making and -breaking interventions.

The dual system framework

Habits have been historically understood as resulting from a balance between goal-directed and **stimulus-driven control** systems [30,31]. The two systems rely on different cognitive representations (Figure 1A) [15]. Goal-directed control guides behavior in a considered way based on current beliefs and goals. This system relies on an understanding of A–O expectancies and valued outcomes (O^V). For example, when a driver approaches a junction, they may consider that turning right will lead them to the store (A–O) where they want to get food (O^V). On the other hand, stimulus-driven control involves behavior that is automatically triggered by familiar contexts or cues based on past experiences. This system involves associations between stimuli and responses (S–R) and might automatically trigger a left turn (R) when the commonly executed response is to go home when approaching that junction (S).

Within this framework, the idea is that contexts and cues often activate habitual tendencies via stimulus-driven control. These tendencies may either align or contrast with beliefs and goals in the goal-directed system (Figure 1B). When both systems align to result in the same behavior (e.g., turning to go home), it becomes challenging to determine which system is ultimately causing the behavior. This ambiguity has led researchers to focus on situations where the systems conflict, defining habits as behaviors that persist even when they contradict current beliefs and

Figure 1. The two control systems. (A) The route home is habitual, guided by stimulus-driven processes, where a specific stimulus (e.g., a tree at a junction) automatically triggers an associated response (e.g., turning left). By contrast, goal-directed actions involve the consideration of action-outcome (A–O) expectancies (e.g., turning right to the store) and the evaluation of valued outcomes (e.g., getting food). (B) When both control systems align, the resulting behavior is the same, making it difficult to determine which system is driving the action. However, when the two systems conflict, habits become evident because they are against explicit beliefs and goals.

goals (e.g., turning to go home despite intending to go food shopping). To differentiate between goal-directed and stimulus-driven control, researchers assess sensitivity to changes in A–O contingencies and outcome values [32]. If behavior persists despite these changes, it is deemed to be habitual, indicating stimulus-driven control (Box 1 discusses the role of goal-directed processes in the causation of habits).

In the dual system framework, habit expression is a dichotomous event that occurs when the strength of the stimulus-driven system is greater than the engagement of the goal-directed system at that moment. To formalize this as an anchor for the present paper, we adopt the perspective that each system has its independent strength, and the competition between the two systems is resolved through a difference of their respective strengths [33] (Box 2 for alternative models). The expression of a habit can be promoted by strengthening the stimulus-driven system or weakening the goal-directed system. Conversely, habits can be discouraged by weakening the stimulus-driven system or strengthening the goal-directed system. In the sections that follow, we discuss how various factors can be used to engineer this balance in a direction that boosts or discourages habit expression (Figure 2).

Box 1. Habits of thought

A contemporary debate concerns the role of beliefs and goals in habits [18–20]. In this paper we adopt the dual system framework in which habits are the behaviors that result when S–R associations outweigh higher-order beliefs and goals. Although this framework has considerable support and has guided the development of the evidence presented in this review, some researchers have argued that it is too simplistic [17,184,190]. It has been posited that behavior emerges from a complex interplay between high-level goals and low-level responses in which habits may be mediated by goals [191]. This is possible because research has shown that the retrieval and selection of goals can itself become habitual (via reinforced stimulus–goal associations) [192], and, similarly, goal-directed computations can also become automatic [184,193,194]. To put this in concrete terms, when encountering a red light, it is possible that the well-trained action of pressing on the brake pedal does not always arise from the stimulus–response (S–R) association (red light → press brake pedal), but instead may be mediated by an automatically activated goal to stop the car (red light → stop the car → press brake pedal) [191]. Well-established stimulus-triggered goals (e.g., red light → stop the car) and action–outcome (A–O) expectancies (e.g., press brake pedal → stop the car) can be considered to be 'habits of thought'. Any behavior performed in the service of that 'habit of thought' may be indistinguishable from behaviors arising directly from S–R associations. For example, in the context of drug addiction, drug taking can be construed as habitual, and drug seeking can still be strongly goal-directed at some levels of behavior, evidenced by the ability to navigate and solve complex problems to obtain drugs [195]. Interestingly, beliefs can also become habitual. Recent research has shown that action slips may occur due to the retrieval of outdated A–O expectancies [21,22] where individuals rely on belief representations that persist even when inaccurate (e.g., momentarily retrieving an old password from memory). The dual system framework has contributed significantly to our understanding of habits and behavior change [196], but acknowledging their complexity opens new avenues for research that can illuminate both the formation and disruption of habits.

Making habits

Habit expression is a complex phenomenon shaped by multiple interacting factors. This section provides an in-depth analysis of the key mechanisms that drive habits. At its core, habit formation relies on strengthening S–R associations through repetition, a process we examine in detail to understand how behaviors gradually become automated. The role of reinforcement is equally crucial; we explore how positive outcomes promote the recurrence of habits over time. As habits solidify, goal-directed processes often take a back seat – a shift we investigate to explain why habits take over in familiar contexts. Environmental stability emerges as a crucial factor in this equation. We discuss how consistent surroundings provide the ideal conditions for habits to flourish and express themselves. Throughout, we integrate relevant neuroscientific findings and highlight their applications in clinical settings, with a particular focus on disorders of compulsion.

Repetition

Repetition is probably the best-known mechanism for habit development and is certainly the longest studied. The **law of exercise** [34] states that each repetition of behavior strengthens S–R associations, thereby increasing the likelihood of its recurrence in the future. With each repetition, neurons representing stimuli and responses fire simultaneously and thereby form connections [35]. Put another way, when a stimulus precedes a response, the neurons encoding these events are believed to establish a memory trace. Therefore, habit expression is expected to increase with repetition. This was initially studied in animals using the outcome devaluation paradigm that is often considered to be the gold-standard measure for habits [15]. In this method, a rat learns to press a lever for a valued outcome (e.g., sucrose pellets). After training, the value of the outcome is reduced (e.g., by creating a taste aversion). The crucial test for habit involves presenting the rat with the lever again to see whether behavior persists despite the reduced value. The impact of repetition on habit expression has been frequently observed in animal research ([15,36–39], *cf* [40–43]). In human studies, the effect of repetition is less clear. Initial research [44] demonstrated that participants expressed more habits after more days of training. However, subsequent studies failed to replicate this, including two preregistered multi-site replication attempts [45–47]. The likely reason for these inconsistencies is that the expression of habit in this test reflects not only the strength of S–R links but also goal-directed computations, which can often overpower the former.

> **Box 2. Alternative models of goal-directed and stimulus-driven control interaction**
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> The interaction between goal-directed and stimulus-driven control has sparked considerable debate, leading to several theoretical models that conceptualize their interplay. One cooperative model suggests that the goal-directed system relies on the correlation rate between action and outcome, whereas the stimulus-driven system is governed by prediction errors generated by contiguous reinforcement [197]. In this model, total response strength emerges from the combined outputs of these two systems. Another approach, the arbiter model, consists of three components: a goal-directed system based on model-based reinforcement learning, a stimulus-driven system based on action history, and an arbiter [68]. The arbiter adjusts the influence of each system, favoring goal-directed control when action–outcome (A–O) contingency is high but favoring stimulus-driven control when stimulus–response (S–R) strength is high. A sequential sampling model addresses habit–goal conflicts by dynamically merging stimulus-driven and goal-directed strengths within a sequential process, thereby eliminating the need for an arbiter [198]. This model posits that stimulus-driven system strength influences the starting point of preference accumulation, whereas goal importance and relevance shape the sampling probabilities of goal-related attributes. In addition, a hierarchical Bayesian model has been proposed in which stimulus-driven strength and reward structures are learned contextually and use probabilistic inference to balance stimulus-driven and goal-directed control [199]. Another hierarchical model suggests that stimulus-driven processes are selected by goal-directed processes as chunked action sequences to achieve specific goals, and that these sequences are executed in a predetermined order irrespective of individual A–O contingencies or values [200]. In summary, these models illustrate the diverse theoretical approaches to understanding the interaction between goal-directed and stimulus-driven control, each highlighting different mechanisms and levels of complexity in behavioral control.

The mixed behavioral findings are mirrored in neuroimaging studies. Although animal research has made considerable strides in advancing our understanding, human studies have yielded equivocal results. In rodents, the dorsolateral striatum has been consistently implicated in S–R learning [39]. Causal evidence comes from lesion studies showing that extensive training leads to habit expression, but not after lesions of the dorsolateral striatum [48,49]. In humans, the corresponding area is thought to be the posterior putamen [39]. One study identified a neural pathway from the posterior putamen to the premotor cortex that was related to individual differences in habit expression on a devaluation test [50] (Figure 3). Another showed that activity in the posterior putamen increased with overtraining [44], and a third decoded action-related activity in the putamen at the time of stimulus presentation [51]. Convergently, the posterior putamen has also been implicated in real-life habits that resemble skills, such as driving [52]. Although these results align broadly with animal studies, recent studies have been unable to replicate some key results [47,53,54]. In many ways this is unsurprising; if researchers struggle to reliably demonstrate habit expression at the behavioral level, it is inherently challenging to study its neural correlates [55].

There has recently been significant progress in addressing these shortcomings [4]. Using a contingency reversal paradigm, where S–R contingencies are switched, instead of outcome devaluation, it was demonstrated that the effect of over-training on habit expression becomes evident in humans only when the time available for response preparation is tightly controlled. When individuals are given ample time – as had been the case in most research to date – even 20 days of training can be insufficient for S–R associations to prevail against higher-order goal-directed processes. This finding is thought to reflect the different processing times of the two systems, where the S–R system is rapidly engaged but goal-directed processing take longer to come online owing to the complexity of the prospective computations required [56,57]. This suggests that habit expression is time-dependent in such a way that habits have a higher probability of being expressed at relatively short response-preparation times when goal-directed control cannot intervene (Figure 4A). Under time pressure, habits are clearly expressed as a function of training duration, systematically increasing from 1 day to 4 and 20 days of training [4]. This suggests that repetition increases the baseline strength of S–R associations, which in turn enhances habit expression (Figure 4B). Importantly, the time-dependent expression of habits has recently been

Making Habits

- Repetition
- Reinforcement
- Stable Context
- Goal-Directed Disengagement

Breaking Habits

- Weakening S-R Links
- Avoiding Habit Stimuli
- Competing S-R Associations
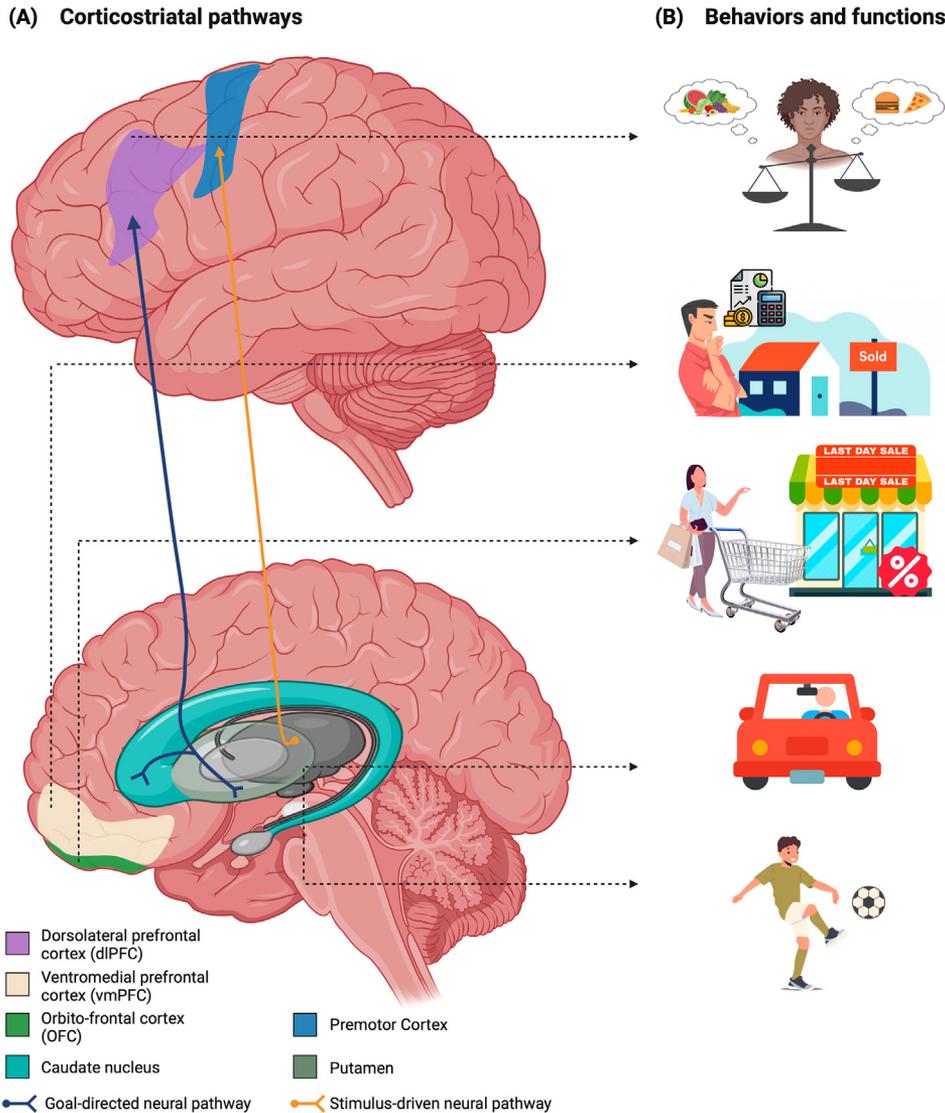- Goal-Directed Inhibition

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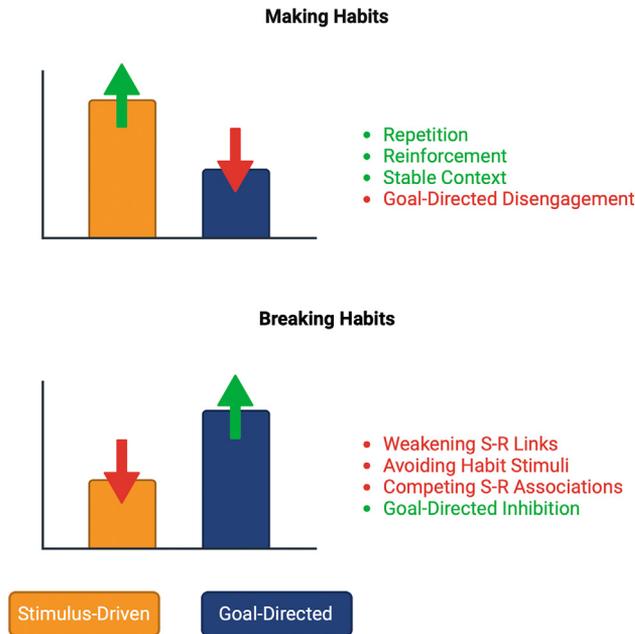
Trends in Cognitive Sciences

Figure 2. Factors for making and breaking habits. Making habits is facilitated by factors that either strengthen the stimulus-driven system or weaken the goal-directed system. Conversely, breaking habits can be achieved through factors that weaken the stimulus-driven system or strengthen the goal-directed system. Abbreviation: S–R, stimulus–response.

replicated several times [21,22,58]. It remains unclear whether the sensitivity to outcome devaluation has the same time-sensitive property [58], although recent work has used this procedure to show that habits of thought can also be revealed at short preparation times [21,22]. That is, there is a tendency to represent older and better-established A–O expectancies when cognitive resources are low [21,22]. This suggests that expectations about the future can also become habitual, not only our actions, highlighting the complexity of the mechanisms underlying habits (Box 1).

Given what we know about the effect of repetition on habit expression, a frequently asked question is – how long does it take to form a habit? Unfortunately, the exact duration necessary to form a habit remains unclear; habit formation can occur rapidly for simple laboratory-based behaviors, sometimes within a single day, provided that a high number of repetitions – up to 1000 trials – are achieved [58]. It is important to distinguish between repetition and time, but current research often fails to effectively separate these factors. Although the exact relationship between repetition and time remains unclear, these factors likely operate through different mechanisms. For repetition, it has been theorized that the associative strength rapidly increases with each reactivation until it reaches a plateau, following an asymptotic growth curve [59–61]. Time likely works through consolidation, a process that is crucial for the formation of S–R memories. Research in rodents has identified that glutamate, particularly in the dorsolateral striatum, plays a key role in this process. Studies have shown that glutamate receptor antagonists can impair consolidation [62], whereas glutamate infusion can enhance it [63]. Although current studies provide useful insights, further research will be necessary to disentangle the specific mechanisms through which repetition and time individually influence habits.

Figure 3. Simplified representation of corticostriatal pathways and brain regions involved in habit expression. The goal-directed pathway extends from the anterior putamen and caudate to the dorsolateral prefrontal cortex (dlPFC), which supports goal-directed control by representing response and outcome identities and comparing the values of different responses. The ventromedial prefrontal cortex (vmPFC) is involved in retrieving goal values and determining their relative preferences, whereas the orbitofrontal cortex (OFC) is sensitive to changes in outcome values. The stimulus-driven pathway extends from the posterior putamen to the premotor cortex, a connection that is associated with individual differences in habit expression during a devaluation test. The posterior putamen has also been implicated in habit formation and expression; it shows increased activity with overtraining, and decoding action-related activity at the time of stimulus presentation. It is further associated with real-life habits that function as skills, such as driving.

In real-life settings, habit formation typically involves fewer daily repetitions over longer periods compared to laboratory settings. Studies of real-life habits show that the nature of the habit itself likely influences the speed of automation; for example, simple handwashing habits in a hospital setting take weeks to form, whereas a regular gym routine often requires several months [64]. Aside from differences in habit complexity, individual differences also play a role in habit formation.
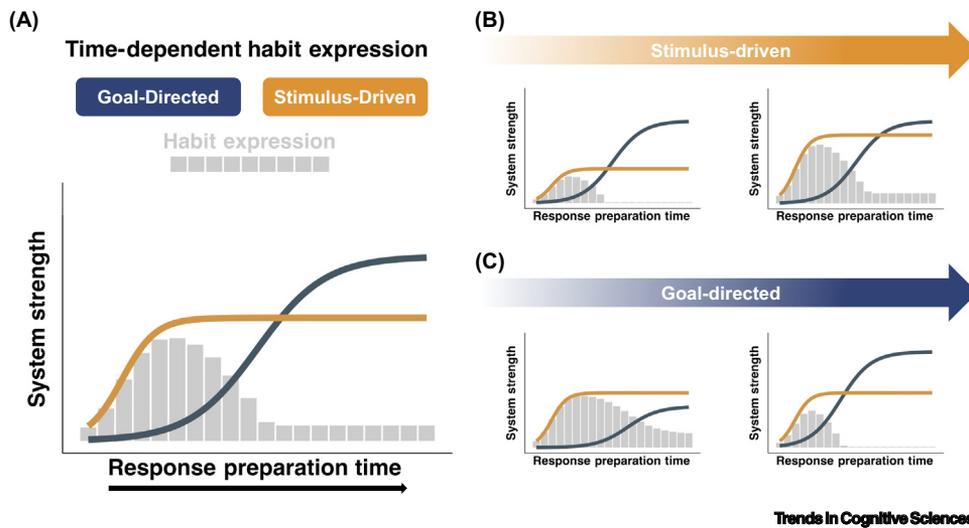
Trends in Cognitive Sciences

Figure 4. Time-dependent interplay and system strength. (A) Habit expression is influenced by response preparation time. The stimulus-driven control system engages quickly, making habit expression more pronounced at shorter response-preparation times. By contrast, the goal-directed system requires more time to engage fully, effectively inhibiting habit expression at longer response-preparation times. (B) The strength of the stimulus-driven system can vary (e.g., increases with repetition), making habit expression more likely, especially at shorter response-preparation times. (C) The strength of the goal-directed system can also vary (e.g., it may be lower under conditions of stress or in individuals with obsessive-compulsive disorder, OCD), leading to increased habit expression, even at longer response-preparation times.

A study on health-related dietary or activity habits found that the duration necessary to form a habit varies considerably between individuals [60]. Participants took anywhere from 18 to 254 days to reach 95% of their asymptote in terms of automaticity, with a median of 66 days. The variability in both the number of repetitions and the time required for habit formation may stem from multiple factors, such as cue intensity and specificity, repetition frequency, and the strength of intrinsic and extrinsic motivations. Unlike laboratory-based paradigms, where many of these factors are controlled, studying habits in real-life contexts involves a complex array of variables. What we know is that, although repetition is important in habit formation, the relationship is not monotonic, and further research will be necessary to clarify how various factors affect this process, particularly in the complex contexts of real-world habits.

Reinforcement

Another key aspect of habits is reinforcement [65,66] (Box 3 for a computational **reinforcement learning** framework of habits). According to the **law of effect** [67], behaviors that are followed by positive consequences are more likely to be repeated in the future by strengthening the S–R association. It is well established that reinforcement facilitates the automaticity of behavior, for instance as indexed by faster reaction times [66]. However, a separate question concerns to what extent this contributes to habits. Because behavioral repetition is typically a natural consequence of reinforcement, it is important to differentiate their impacts on habits [68]. To this end, one study [69] manipulated both the amount of training and **reward magnitude**. Capturing the time-dependent nature of stimulus-driven and goal-directed processing, they operationalized habits as reaction time switch costs (an indicator of S–R interference), which is the time it takes to emit a response different from the response that was originally trained. They found that reaction time switch costs were more pronounced after overtraining, but were also higher for associations that were previously linked to higher-value outcomes. Further evidence for this is provided by research using an associative learning task that

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Box 3. Model-based and model-free reinforcement learning

Some have linked stimulus-driven and goal-directed control to the computational framework of reinforcement learning. Specifically, there has been a conceptual mapping of model-based decision making onto goal-directed control and **model-free control** of decision making onto stimulus-driven control [19]. Model-based planning is a computationally intensive mode of action selection that entails generating (and comparing) prospective representations of state–action–state transitions to arrive at a choice. Empirical studies have shown that individual differences in model-based control correlate negatively with habit expression, supporting the view that model-based planning is a useful formalization of some aspects of goal-directed processing [76–78]. Model-free processing, by contrast, describes how action values are cached based on history of reinforcement, independently of a broader and more accurate model of the world. The crude but efficient nature of this type of learning bears resemblance to the rigidity of stimulus–response associations, but several studies have shown that individual differences in model-free learning are not themselves predictive of habit expression ([76–78]; *cf* [201,202]). Moreover, model-free control still depends on values and thus differs from stimulus-driven control [68].

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could differentiate between repetition-based effects and reward-based effects of choices [70]. Results supported independent impacts of both repetition and reward on choices, suggesting that the mere performance of a behavior (absent value) influences its likelihood of recurrence, but that this is more pronounced under conditions of greater reinforcement. These findings suggest that the willful promotion of habit in everyday life might be achieved through strategic reward-tagging of actions that one wishes to render habitual – for example, recording and tracking rewarding exercise outcomes, as is common in many commercial fitness apps [71].

The role of reinforcement in habits has been consistently linked to dopamine [72,73], and causal evidence from rodent studies shows that lesions of the nigrostriatal dopamine system that project onto the dorsal striatum disrupt S–R learning [74]. It is thought that during habit formation there is an increase of dopamine activity in the stimulus-driven dorsolateral striatum, and a concurrent decrease in the goal-directed dorsomedial striatum [75]. However, this regional specificity of dopamine has been challenged, and indeed it has been found that dopamine activity in both regions remains stable throughout training [76]. Thus, although dopamine clearly is an important neurotransmitter in S–R learning, future work will be necessary to shed light on the exact mechanisms. Given the likely role of dopamine, examining medical conditions associated with dopamine dysregulation, for example Tourette syndrome (Box 4) and Parkinson's disease, may offer valuable insights for future research [77–79].

Disengagement of goal-directed processes

Another way that habits can be promoted is through the disengagement of goal-directed processes. As previously highlighted, adding time constraints is an effective method to diminish the role that goal-directed processing plays in behavior. Similar effects have been observed by imposing working memory demands [80], inducing acute stress [81,82], and causing sleep deprivation [83], although some studies have reported conflicting results [84–87]. It may follow that other methods that decrease cognitive engagement, such as distraction (e.g., listening to podcasts), could be helpful for promoting habit formation. Interestingly, goal-directed disengagement may do more than merely affecting habit expression: if applied during initial learning, it may promote the development of S–R links [21,69,88]. In addition, it has been demonstrated that, under stress, neural representations of S–R associations become more robust, whereas representations of A–O connections weaken [89]. Importantly, these neural representations were independently associated with habitual responding, further supporting the dual system account.

Causal evidence for the role of goal-directed associations in habit expression comes from studies that selectively deactivate goal-directed brain regions of the cortex and dorsal striatum [39].

Box 4. Habits and transdiagnostic psychopathology

Research has linked deficits in goal-directed control to several disorders (Figure 4C, low goal-directed strength), most prominently obsessive-compulsive disorder (OCD), but also substance addiction and aspects of compulsive behavior seen in binge eating disorder [145]. Recent work has demonstrated that these observations can be best explained via the existence of a transdiagnostic compulsivity dimension that is evident in the general population [105,203–205], as well as in a patient sample [206]. Much less is known about how individual differences in the formation of rigid stimulus–response (S–R) associations might relate to psychopathology. One possibility is that disorders characterized by more simple motor repetition may involve an overactive S–R system (Figure 4B, high S–R strength). Specifically, it is possible that repetitive behavior such as tics, flapping, and body-focused repetitive behaviors (BFRBs), including skin picking and hair pulling, may stem from a vulnerability to accelerated S–R learning. Evidence for this idea comes from commonalities in the neurotransmitters implicated in habit formation and expression [207] and these conditions, particularly dopamine and GABA in Tourette's syndrome [208,209] as well as in BFRBs [210,211]. Interestingly, comorbidity between tics and OCD is common [212,213], highlighting the likely complex interplay between the systems of control. To complicate things further, addiction-related pathologies often begin with deficits in goal-directed control but shift over time towards greater influence by an over-active stimulus-driven system in animal studies [92], but evidence in humans has been mixed [23,187]. Understanding the precise mechanisms behind rigid, compulsive-like behaviors in psychiatry is crucial because it may help to determine which treatment is most suited to a given patient. With recent advances in methodology, these insights are on the horizon.

Inactivation of these regions causes habits to be expressed (devaluation failures) even if the rats received only minimal training [90–92]. These goal-directed computations are multidimensional and involve various brain regions. In humans, a corticostriatal pathway, extending from the anterior putamen and caudate to the dorsolateral prefrontal cortex (dlPFC), has been consistently implicated [33,47,53] (Figure 3). The dlPFC supports goal-directed control in various ways, such as representing response and outcome identities [51], as well as comparing values of different responses [93]. Moreover, the ventromedial prefrontal cortex (vmPFC) is involved in retrieving goal values and determining their relative preference [94], as well as in capturing the values of executed responses [95]. Finally, the orbitofrontal cortex (OFC) is involved in the sensitivity to changes in outcome values [96]. One operationalization of these collective mental functions is **model-based planning** (Box 3) which several studies have shown to be associated with individual differences in habit expression [97,98]. Conditions known to promote habits, such as working memory load and stress, have been found to decrease activity in these brain areas in the PFC [99,100], further supporting the link between reduced goal-directed control and increased habit expression.

Research on clinical disorders of compulsion, in which disturbances to frontostriatal circuits are strongly implicated (e.g., OCD [101–104]), further align with this perspective. OCD patients show increased habit expression during devaluation tests, even after only modest training [5,6]. An accumulation of evidence now suggests that these habits arise, at least in part, due to deficits in goal-directed control, without the need to evoke any acceleration or hyper-activity of S–R learning [105,106] (Figure 4C). Neuroimaging studies in OCD patients and healthy participants on a spectrum of compulsivity have found that devaluation performance (i.e., habit expression) is linked to problems representing A–O relationships [107] and aberrant activity in the caudate [108]. Together, these studies add weight to the idea that disrupting goal-directed control results in greater habit expression.

Stable contexts

A special extension of goal-directed attentional mechanisms, as described above, concerns the role of context in habit expression. In real-world settings, individuals may initially have detailed representations of the outcomes that are associated with their actions. However, through repeated engagement in a behavior in a consistent environment and with predictable reinforcement, individuals are thought to gradually devote less conscious attention to the execution of the behavior, leading to diminishing of goal-directed control [28,109,110]. This phenomenon is supported by self-report data of real-life habits such as tooth brushing in the bathroom, showing that behavior and

conscious thoughts are often not aligned [111]. It is thought that the context signals the stability of reinforcement, suggesting that goal-directed control may not be required. This understanding suggests that, to express new habits effectively, one should aim to consistently perform the desired behavior in a stable context with predictable outcomes, thereby allowing the action to gradually shift from conscious, goal-directed control to more automatic, stimulus-driven execution.

Because stable contextual cues reduce the need for action monitoring, they also promote chunking – the integration of multiple actions into a sequence (e.g., an experienced driver changing gears in a manual car) [112]. Chunking has been shown to be dopamine-dependent [113,114]. This may explain why patients with Parkinson's disease, which is associated with a loss of dopamine, often experience difficulties in chunking [115]. In rodents, habitual action sequence execution is marked by increased activity in the stimulus-driven dorsolateral striatum and decreased activity in the goal-directed dorsomedial striatum [112]. Similarly, stable cues and reduced action monitoring facilitate habit stacking, a strategy where new habits are linked to existing ones (e.g., flossing after brushing teeth) [116]. In habit stacking, the old habit serves as a cue for expressing the new habit [117,118]. Both chunking and habit stacking leverage the tendency of the brain to combine actions and respond to contextual cues, thereby facilitating the formation and maintenance of new habits.

The important role of context in habit expression is even more apparent when a habit has been trained in one context but must be performed in another [28,119]. This is particularly relevant because real-life situations are often dynamic and unpredictable, presenting challenges for habits that have been formed in specific, stable environments. In such a situation, habit expression is reliably weaker [120]. Similar findings emerge from studies of real-world habit-like behaviors. For instance, one study observed a decrease in exercise frequency in students following transitions to a new university, especially among individuals with stronger exercise habits [121]. Similarly, it has been found that switching contexts led to lower automaticity and frequency of study habits in students as well as for self-selected habits in users of a habit-builder app [122]. This suggests that habits are deeply context-dependent [119]. However, a context switch does not entirely eliminate existing habits [120]. This makes sense, of course, when we understand contexts themselves as a complex set of multisensory cues [123]. In this light, habits can be seen as resulting from various environmental cues that trigger specific S–R associations. Ideally, we aim to cultivate (good) habits that are robust across various contexts, thereby avoiding dependency on specific environmental cues. Thus, forming a habit in multiple contexts may increase the likelihood that it transfers to other contexts because of shared cues [124,125].

Breaking habits

In this section we discuss several key strategies that can effectively break the cycle of maladaptive habits and foster behavioral change. We begin by examining techniques aimed at directly weakening S–R associations – the foundation of habits. We then explore the crucial role of the environment, focusing on how avoiding habit-related cues and altering one's surroundings can support the habit-breaking process. We also investigate methods to enhance goal-directed inhibition, thereby empowering individuals to override automatic responses in favor of more deliberate, adaptive choices. Finally, we discuss the potential of establishing competing S–R associations as a means to supplant old habits with new ones. Throughout this section we consider the underlying neural mechanisms at play and highlight the clinical considerations and implications.

Weakening S–R links

Although significant attention has been devoted to understanding habit formation and its behavioral manifestations, there are open questions concerning how to effectively break established

habits and how behavior change strategies and interventions can be developed based on this [12]. A primary obstacle in breaking habits lies in the enduring nature of existing S–R associations. Extinction studies show that refraining from a response does not erase pre-existing associations but instead creates a new association that links the extinction context to a lack of response [119,124]. Old memories are especially likely to be retained when there are abrupt changes [126,127]. In the case of habits, these changes can be external, such as environmental shifts (e.g., a regular route to work is blocked), or internal, such as motivational changes (e.g., deciding to diet or abstain from taking drugs). Motivational changes are often initiated suddenly based on temporal landmarks, such as the start of a new year, a phenomenon known as the 'fresh start effect' [128]. However, although these abrupt changes may spark initial motivation, they can also leave old S–R associations intact, making individuals susceptible to reverting back to old habits and experiencing relapse over time [129].

Despite challenges, recent studies have revealed promising methods to weaken S–R links. Clinical trials, pharmacological research, and translational experiments have produced encouraging results. In patients with Tourette disorder it has been shown that CBIT (comprehensive behavioral intervention for tics) reduces activity in the putamen [130]. This suggests that behavioral therapy may help patients to suppress the involuntary tics characteristic of Tourette disorder by weakening the S–R associations that these tics are speculated to depend upon. In rodents, it has been shown that the dorsolateral striatum may be not only involved in the formation and consolidation of S–R links but also in their extinction [131,132]. Indeed, administration of the glutaminergic receptor agonist D-cycloserine in this area enhances extinction of S–R links [133]. In rodents, this antagonist has been shown to successfully facilitate the extinction of cocaine-seeking behavior [134]. In humans, it has been shown to increase efficacy of behavioral therapies in patients with OCD ([135,136]; *cf* [137]) and Tourette Disorder [138]. Although D-cycloserine shows potential for improving treatments, there is a need to focus on identifying specific treatment moderators [139].

Avoidance of habit stimuli

Habits are context-dependent, and therefore one way to break habits is to avoid contexts that contain habit stimuli, also referred to as habit cue discontinuation [12,140]. Indeed, a switch to a different context has been shown to revert behavioral control from stimulus-driven to goal-directed [28,119,141]. Actively avoiding known habit stimuli, also known as stimulus control, has proved to be applicable across a spectrum of habitual behaviors, encompassing body-focused repetitive behaviors, dietary patterns, smoking, and gambling disorders [142–145]. For example, someone trying to quit smoking might use situation-selection strategies by avoiding environments where they used to smoke, such as bars or social gatherings where smoking is common [146]. This individual approach to creating friction against unhealthy habits can be scaled up and complemented by broader public health initiatives [147]. Such large-scale efforts might include implementing public smoking bans or restricting alcohol advertisements. These measures can help to prevent habits triggered by S–R associations, but it is important to note that people will still engage in the unhealthy behavior if they feel sufficiently motivated or compelled [19,23].

Given the importance of situation selection strategies for controlling habit expression, it is no surprise that an ideal time to curtail habits is following major changes [116], such as a relocation or new job [117], when many cues and contexts change at once. Unfortunately, habits are a two-way street: although these major life events provide an opportunity to break unwanted habits, they have also been shown to disrupt positive habits such as exercise adherence [118]. Moreover, a key challenge is that, if triggering contexts or cues are encountered again, they can lead to relapse, for instance of drug-seeking behaviors [148]. Complicating matters further, contexts are multifaceted and cues can appear in multiple contexts; some stimuli may prove to be difficult to avoid entirely

[124]. Indeed, it is important to acknowledge that stimuli can be both external, which can be physically avoided, and internal (e.g., emotional states), which are more challenging to evade. Thus, successfully breaking a habit often requires a nuanced approach that addresses both external and internal stimuli while considering the complexities of individual and contextual factors [149].

Goal-directed inhibition

Recognizing the persistence of S–R associations, the goal-directed inhibition of these established connections emerges as a key strategy to break habits [150]. Goal-directed habit inhibition can be facilitated in two ways. First, by actively avoiding conditions that weaken goal-directed strength, especially in contexts that contain habit stimuli. Generally, individuals perform well at inhibiting overtrained responses [45–47,58]; however, as outlined above, goal-directed capacities can be compromised under conditions such as time pressure [4], working memory load [80], and stress [81,82,88,151–153]. Such conditions should be avoided in the service of breaking maladaptive habits. A longitudinal study showed habit expression in chronically stressed participants, but, importantly, habit expression ceased after a 6 week stress-free period [154]. Moreover, the stress effects on habits were related to decreased activity in a goal-directed frontostriatal pathway involving the medial PFC and caudate. However, the influence of these conditions is also subject to individual differences, for instance in working memory capacity, where high capacity is protective of goal-directed control under stress [155,156]. Second, goal-directed habit inhibition may be facilitated by directly strengthening the goal-directed system. For instance, goal simulation – a component of episodic future thinking that involves envisaging future goals – has been suggested to have therapeutic effects on addictive behaviors [157]. Moreover, goal-directed processes are sensitive to motivation to engage in them [158], and motivation-based feedback in combination with monetary incentives may serve as potent catalysts in boosting habit inhibition [159]. This aligns with findings in contingency management – an intervention that involves providing tangible rewards or incentives to individuals contingent upon meeting specific behavioral goals that are typically related to abstinence or adherence to treatment protocols [160–162]. In fact, contingency management is one of the most effective interventions for substance use disorders [163].

Goal-directed inhibition is also clinically recognized: inhibition constitutes a core component of exposure therapy for anxiety disorders and OCD where individuals are systematically exposed to triggering stimuli and tasked with refraining from habitual responses [164,165]. In cognitive behavioral therapy sessions for OCD, patients are taught to recognize intrusive thoughts and actively choose not to engage in compulsive behaviors, thus breaking the habit loop [166]. Importantly, the efficacy of these therapies can be further increased through non-invasive stimulation of dlPFC and vmPFC owing to their role in inhibition [167]. Indeed, transcranial direct current stimulation targeting the dlPFC has been shown to increase proactive control, which involves maintaining goals to prepare for anticipated cognitive demands [168]. In studies of individuals with substance use disorder, the dlPFC is the most frequent target, and has shown promising results for enhancing cognitive control in this population [169]. In summary, integrating goal-directed inhibition techniques with non-invasive brain stimulation may enhance cognitive control across a wide range of disorders, potentially leading to more effective treatment outcomes.

Competing S–R associations

Inhibiting stimulus-driven tendencies can be effective, but this way of intervening does not directly break down the strength of the S–R link [170]. Moreover, inhibition alone may be prone to relapse under time pressure, stress, or distraction. Thus, a possibly more effective approach is the formation of a new competing habit, also known as habit substitution [140]. One way to do this substitution is through **implementation intentions** (if–then plans) that link anticipated contexts and

cues to responses ('if situation X occurs, then I will do response Y') [171]. Implementation intentions have been described as instant habits which are installed through a single instance of strategic goal-directed control [172]. Indeed, implementation of novel habits relies on the goal-directed pathway from the caudate to the dlPFC [54]. The efficacy of implementation intentions has been shown in reducing habitual errors in the laboratory [173] and in reducing real-life behaviors such as alcohol consumption and smoking [174], unhealthy eating [175], sugar-sweetened beverage consumption [176], and bedtime procrastination [177]. Thus, by associating a behavioral intention with a specific future context, implementation intentions offer a robust method for creating new habits and overcoming unwanted ones.

The formation of competing S–R associations is central to habit-reversal therapy for the treatment of tic disorders, Tourette syndrome, and body-focused repetitive behaviors [178,179]. This form of intervention involves multiple stages, including awareness training to identify triggering stimuli or bodily cues, habit response detection and prevention, and the installation of competing responses [165]. A similar intervention termed script elicitation has recently been shown to be successful in improving sleep hygiene habits [180]. In a one-on-one interview, participants work out a detailed description of their sleep routine, thereby increasing their awareness of potential triggers, and then establish an alternative routine. Because these interventions combine engaging in goal-directed control and a competing habit, it is not surprising that they are proving to be effective. Indeed, habit reversal therapy is one of the most successful treatments for body-focused repetitive behaviors [181].

Concluding remarks

Habits have been captivating psychologists for over a century and have experienced a surge in interest in recent decades. The interest in habits arises from an increasing awareness about their centrality in everyday life, for better or worse, and their role in disorders of compulsion. We have described the dual system framework of habits and outlined the latest developments in its implications for habit formation and modification. In this framework, habits can be understood as a balance between stimulus-driven and goal-directed control. Although significant strides have been made in understanding goal-directed control, our grasp of stimulus-driven control is only just developing [55,182], and future research that concentrates on this holds promise for identifying the precise neural computations that support behavioral autonomy, elucidating its role in new aspects of psychopathology, and devising interventions that directly target S–R associations (see Outstanding questions).

Although the dual system framework offers a useful perspective on habits, it is important to acknowledge that it may not fully capture their complexity (Box 1). In this framework, the goal-directed system primarily serves to control habitual tendencies. However, other frameworks emphasize goal-directed processes as the primary determinants of behavior [19,183,184]. Indeed, some real-life habits may primarily involve goal-directed processes, which may explain why individuals struggle to maintain beneficial established habits when their beliefs and goals change [185]. For example, a person who exercises every morning might sustain this habit not only through S–R associations (e.g., the alarm clock prompts a workout) but also through consistent alignment with personal goals such as health and increased energy. When life circumstances change, such as becoming a parent, this habit might wane not simply because of disrupted cues but because it no longer aligns with new priorities and circumstances.

Recognizing the complexity of habit mechanisms may also help to explain some of the mixed evidence linking habits studied in the laboratory to those observed in real life [17,70,186]. To better understand habit dynamics, future research should aim to map specific habit mechanisms

identified in the laboratory to their real-life counterparts. For instance, habits may differ in their sensitivity to changes in A–O contingencies and outcome values, and the mechanisms involved likely map onto different real life-habits [187]. Indeed, performance in contingency degradation and outcome devaluation tasks often does not correlate [70]. Such efforts could open new avenues for advancing our understanding of how to successfully make and break habits.

Beyond the complexity of habits, a significant challenge for habit research has been the failure to replicate key findings (e.g., [46,47,85,86]). For instance, showing that habit expression is a function of training has proved to be difficult. We take the position that many of these issues stem from the conflation of S–R learning, goal-directed processes, and the expression of habit. In cases where mechanism and task are aligned, we see good agreement across paradigms. For example, evidence that devaluation performance depends on model-based planning [97,98] and explicit goal-directed knowledge [5]. However, given the finding that habits can be reliably unmasked by manipulating response preparation time [4,21,22], future research may be able to identify the neural correlates of the stimulus-driven system and shed light on the temporal dynamics in relation to goal-directed control. This will be crucial for estimating S–R associative strength independently of habit expression. Reliably demonstrating habits and establishing neural signatures holds significant implications for understanding psychopathological disorders. Although much research has centered on deficits in goal-directed control [7,188], it is conceivable that some disorders involve a dysfunctional S–R system [9,189] (Box 4). In sum, recent research has provided many new insights into how we can make and break habits, but to make further progress it is important to dissect the different underlying mechanisms and tailor interventions precisely.

Declaration of interests

The authors declare no competing interests.

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