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THE RELATIVE CONTRIBUTION OF GOAL-DIRECTED AND HABIT SYSTEMS TO PSYCHIATRIC DISORDERS

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SUMMARY

Psychiatric disorders may be caused by underlying imbalances between goal-directed and habit systems in the brain. Numerous studies have aimed to establish whether this is because of a goal-directed system deficit, enhanced habit system, or both. This transdiagnostic approach to studying psychiatric disorders is increasingly popular. Maladaptive habitual behaviour is present in many disorders. It is the principal observation in disorders of compulsivity and is also present in other psychiatric disorders that are not primarily characterised by compulsive behaviour. The psychopathology that causes these disorders might be similar and could be targeted with specific treatment. Traditional categorical classification systems of psychiatric disorders do not reflect similarities in neurobiological dysfunction. The comorbidity and overlap between psychiatric disorders means that a dimensional classifications system based on underlying brain system dysfunction might be more appropriate.

In this paper, the neural and neuromodulatory systems that contribute to goal-directed and habit systems are discussed. Account is taken of model-based and model-free computational learning mechanisms that are thought to give rise to goal-directed and habitual control respectively. Different psychiatric disorders that have a deficit in goal-directed behaviour or habit systems are then explored to see if there are similarities in the underlying neural systems despite differences in clinical presentation. It concludes that the relative contribution of goal-directed and habit systems in psychiatric disorders is not evenly distributed. Similar dysfunction of these systems might cause different psychiatric disorders. This neurobiological finding might influence classification systems and research into potential treatments.

Key words: *psychiatric disorders - goal-directed systems in brain - habit systems in brain - maladaptive habitual behaviour - disorders of compulsivity – comorbidity - dimensional classifications system - neural and neuromodulatory systems*

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Introduction

According to dual-system theories, instrumental behaviour can be governed by two dichotomous forms of action control (Dickinson & Balleine1994): a flexible goal-directed system and a rigid, repetitive habit system. Contingency learning, incentive learning and the stimulus-response (S-R) association mechanism are the three learning processes that contribute to instrumental action (Balleine & Dickinson 1998). Goal directed action is controlled by contingency learning, which encodes the relationship between the action and the outcome, and incentive learning, which forms a representation of the outcome value. Habitual action is controlled by the reflexive S-R mechanism which does not rely on the action-outcome (A-O) association to guide choice and is driven by external cues (Balleine & O'Doherty 2010). These opponent motivational systems enable us to respond to different environmental demands. The goal-directed system is able to flexibly adapt to permanent environmental changes (Banca et al. 2015) but is effortful to sustain (Adams 1982). The habit system allows for automatic, more efficient responses (Banca et al. 2015), but can lead to behavioural inflexibility after overtraining (Adams 1982). Goal-directed and habit systems may independently control or exert synergistic cooperative control over choice performance (Balleine & O'Doherty 2010). Over-reliance on the habit system and/or under-reliance on the goal-directed system may underlie several psychiatric disorders (Gillan et al. 2011).

The goal-directed and habit systems differ in their sensitivity to changes in the value of an outcome and to changes in the A-O contingency (Balleine & O'Doherty 2010). Outcome devaluation and contingency degradation tests distinguish between the two systems. They establish which system is controlling behaviour in different circumstances. An outcome devaluation paradigm was first described by Adams and Dickinson (1981). They trained rats to press a lever in return for sucrose. The sucrose was then devalued through taste aversion, pairing it with an injection of lithium chloride. A subsequent extinction test showed reduction in lever pressing in response to changes in motivation. In humans, outcome devaluation is most commonly achieved through selective satiety (Tricomi et al. 2009). In both humans and rats, overtraining led to insensitivity to outcome devaluation and automaticity of behaviour (Tricomi et al. 2009, Balleine & O'Doherty 2010). Performance became more reliant on an S-R process rather than A-O association, suggesting that behaviour which was initially goal-directed was now controlled by a habit system. Contingency degradation is based on the

fact that A-O learning is not determined by simple contiguity, whereas this is key to S-R learning (Balleine & O'Doherty 2010). S-R learning should therefore be insensitive to non-contiguous delivery of the outcome. Free rewards are presented without the action having taken place, for example, food may be given without the rat having to press the lever (Dickinson & Balleine 1994). These two behavioural assays determine whether outcome-insensitive behaviour is present but are unable to decipher whether this is caused by strengthening of S-R habits, weakening of goal-directed behaviour, or both (Gillan et al. 2015).

Reinforcement learning

Reinforcement learning is driven by two dissociable computational processes which are known as model-based and model-free reinforcement learning (Sutton & Barto 1998). These learning algorithms map somewhat onto goal-directed and habit systems respectively. Successful decision-making is designed to maximise reward and minimise punishment. Each computational process uses a different strategy to achieve this. The model-free mechanism learns through a temporal difference error teaching signal (Sutton & Barto 1998) and relies on retrospective experience of the value of an action. Model-based learning is prospective and assesses future outcomes of a given decision using a learned cognitive map (Tolman 1948). Model-based learning is more flexible and sensitive to environmental changes than model-free learning. In a sequential decision task, Gillan et al. (2015) showed that individual differences in model-based learning predicted subsequent sensitivity to outcome devaluation, one of the key features of goal-directed behaviour. Although there is clear evidence for the link between model-based learning and goal-directed control, the exact mapping of model-free learning onto the habit system is more controversial. One study found that habit formation and model-free learning may be entirely unrelated (Dezfouli & Balleine 2013). This was supported by Gillan et al. (2015) who found that a model-based strategy may protect against habit formation but the amount of model-free learning did not predict dominance of habits. Model-free learning shows no relationship to devaluation sensitivity (Gillan et al. 2015). There is also limited evidence that model-free learning and habits are neurally related (Daw & O'Doherty 2013). Many studies use reinforcement learning models to measure habitual behaviour based on model-free learning directly, so it is important to consider the potential weaknesses of this model. Despite this, the balance between model-based and model-free behaviour is suggested to determine the competition and cooperation between goal-directed and habit systems (Daw et al. 2005). Voon et al. (2014) found that dysfunction of a neurocomputational mechanism involving model-based learning may underlie many psychiatric disorders involving compulsive behaviour.

It is important to describe the interaction and organisation of goal-directed and habit systems in order to understand how they might contribute to psychiatric disorders. The flat architecture predicts that the goal-directed and habit systems operate in parallel and their degree of utilisation is coordinated by an external arbitrator (Griffiths et al. 2014). Dezfouli and Balleine (2013) proposed an alternative hierarchical system where a global goal-directed system is in control and selects between goal-directed actions and faster habitual sequences. A two-stage decision test showed that a habitual action being selected in the first stage predicted another habitual action being selected in the second stage to form a predetermined habitual sequence (Dezfouli & Balleine 2012). The flat architecture would predict that the action selected in the second stage is independent of the action selected in the first stage. However, the action selected in the second stage is dependent on the action selected in the first stage. This contradicts the flat architecture organisation. In the hierarchical model, the goal-directed system functions at a higher level. It is able to use a habit to achieve the goal and then regain control. Failure of the goal-directed system to take back control and override the habit system could result in psychiatric disorders.

Neural systems underlying goal-directed and habitual behaviour

Goal-directed and habit-systems are underpinned by distinct corticostriatal networks (Delorme et al. 2015). Homologous neural substrates in rats, monkeys and humans are implicated in each system. There are discrepancies between neural substrates in rats and humans which may be revealed by experiments on monkeys. However, these studies tend to take longer and be more complicated than studies using rats.

In rats, the structures underling goal-directed learning are the prelimbic region of the prefrontal cortex (Balleine & Dickinson 1998) and the area it projects to, the dorsomedial striatum (Balleine 2007). Lesions to the prelimbic area before initial training caused rats to become insensitive to outcome devaluation (Ostlund & Balleine 2005). This suggests that the prelimbic area is important for acquisition of goal-directed behaviour. In contrast, the dorsomedial striatum appears to be necessary for both acquisition and expression of goal-directed behaviour (Yin et al. 2005). The proposed human homologues for these areas are the ventromedial prefrontal cortex, including the medial orbitofrontal cortex and the medial prefrontal cortex, and the anterior caudate nucleus (Balleine & O'Doherty 2010). A disposition towards model-based choice correlated with grey matter volume in the ventromedial prefrontal cortex and caudate nucleus (Voon et al. 2014). The medial and central orbitofrontal cortex was identified in a functional magnetic resonance imaging (fMRI) study by Valentin et al. (2007) who found it to be sensitive to the incentive value of actions. Gläscher et al. (2009) confirmed that the reward representations

were driven by A-O associations and that the ventromedial prefrontal cortex is involved in the goal-directed system. Similarly, Tanaka et al. (2008) measured areas that were sensitive to A-O contingency and found that the ventromedial prefrontal cortex and the anterior caudate nucleus were activated. Experiments in monkeys have also confirmed that the caudate nucleus represents A-O contingencies (Lau & Glimcher 2007). Within the monkey orbitofrontal cortex, areas 11 and 13 contribute to devaluation effects (Murray et al. 2015) and aid in goal-directed selection of actions.

As demonstrated by lesion studies in rats, habit formation is mediated by the dorsolateral striatum (Yin et al. 2006) and the infralimbic region of the prefrontal cortex (Liljeholm et al. 2015). Tricomi et al. (2009) discovered the human homologue of the dorsolateral striatum using fMRI. Participants were overtrained and tested using outcome devaluation to reveal that their behaviour was habitual. Activity in the posterolateral putamen increased as behaviour become autonomous. The infralimbic cortex in rats has been proposed to be homologous to the subgenual cingulate cortex in humans because of its connections to the nucleus accumbens and amygdala. However, the functions of these homologous structures are different (Liljeholm et al. 2015). Increased white matter tract length between the putamen and premotor cortex predicts habitual behaviour whereas the strength of connectivity between the ventromedial prefrontal cortex and caudate nucleus predicts goal-directed behaviour (de Wit et al. 2012). There are relatively conserved structures involved in goal-directed and habitual control in rats and humans, but there has been insufficient research into prefrontal cortex functions using comparable tasks (Balleine & O'Doherty 2010).

The amygdala plays a fundamental role in mediating between goal-directed and habit systems. The basolateral amygdala encodes the incentive value of a reward via sensory-emotional association (Corbit & Balleine 2005). It has close connections with the orbitofrontal cortex to control goal-directed action (Stefanacci & Amaral 2002). In contrast, the central nucleus of the amygdalais thought to partly control the dopaminergic projections from the substantia nigra to the dorsolateral striatum (El-Amamy & Holland 2007), perhaps supporting habitual control. The amygdala can produce dissociable effects on behaviour. The nucleus accumbens is part of the ventral striatum and is involved in reinforcement learning, motivation and reward. It receives input from the orbitofrontal cortex and basolateral amygdala and controls input to the basal ganglia to allow or prevent performance of an action (Groenewegen et al. 1999). The nucleus accumbens and the associated mesolimbic dopamine system reinforce the effects of addictive drugs (Roberts & Koob 1982).

Chemical neuromodulatory systems underlying goal-directed and habitual behaviour

Neuromodulatory systems influence the balance between goal-directed and habit systems. Dopamine is a neurotransmitter in the brain involved in reward-motivated behaviour, learning and motivation (Wise 2004). Phasic dopamine firing in the ventral corticostriatal circuit acts as the reward prediction error signal in model-free reinforcement learning to signal the expected value of an outcome (Schultz et al. 1997). Although model-based learning does not use this error signal, it may still be sensitive to and influenced by dopaminergic function (Sharp at al 2015). Dopamine has a large role in learning initially but can cause permanent changes in synaptic plasticity. It appears to have a smaller role in response expression with extended training until behaviour is dopamine-independent (Wickens et al. 2007). This represents the shift from goal-directed to habitual control of behaviour.

Nelson & Killcross (2006) examined whether sensitisation of dopaminergic systems using amphetamine led to increased S-R habits. Amphetamine mimics overtraining. An outcome devaluation procedure using selective satiety was carried out. Amphetamine was administrated before or after training. The rats which had been administered amphetamine before the training were insensitive to the changed value of the reinforcer. The presence of habitual responding suggests that amphetamine disrupts the acquisition of goal-directed actions and enhances model-free learning through increased dopamine neurotransmission. This may be achieved through dopamine-mediated long-term potentiation (Wickens et al. 2007). Lesions of the nigrostriatal dopaminergic pathway from the substantia nigra to the dorsal striatum disrupt habit formation even with extensive training (Faure et al. 2005). This demonstrates the importance of dopamine in promoting model-free learning.

Two studies conflict with the theory that dopamine leads to enhanced habitual behaviour. Wunderlich et al. (2012) investigated the modulatory role of dopamine in the arbitration between model-based and model-free control. L-DOPA, a precursor of dopamine, was found to enhance model-based behavioural control but not through a disruption of model-free control. They postulated that the cognitive processing ability of dopamine might lead to a transition towards model-based control. This is surprising and contradicts many other studies. It may be that dopamine promotes model-based learning in low doses that were used in this study, but in higher doses might promote model-free learning. It is unfeasible to test high L-DOPA doses on humans because of ethical issues. De Wit et al. (2012) made a similar finding. Acute dietary phenylalanine and tyrosine depletion (APTD) reduces dopamine globally. After an initial instrumental learning stage where participants had to respond to stimuli to gain rewarding outcomes, an outcome devaluation test and a slip-of-

action test were used to establish whether behaviour was goal-directed or habitual. APTD had no effect on A-O or S-R learning but behaviour in female volunteers was found to be habitual in the slip-of-action test. In this test, participants must respond to stimuli that are still valuable and withhold responses to devalued stimuli. Dopamine depletion led to an increased reliance on the S-R habit system at the expense of the goal-directed system. This study is seemingly in conflict with Faure et al. (2005) and Nelson & Killcross (2006). However, it may be that the APTD caused enhanced dopamine depletion in the goal-directed ventral corticostriatal circuit and ventromedial prefrontal cortex rather than the parallel habitual nigrostriatal pathway. As in the study by Wunderlich et al. (2012), dose-dependent effects may have influenced the results. Faure et al. (2005) lesioned the nigrostriatal pathway using 6-hydroxydopamine (6-OHDA), which causesan extremely high level of dopamine depletion in the dorsal striatum. APTD would have caused significantly less depletion more globally. Further dopamine depletion may have compromised the habit system. Only female volunteers displayed habitual behaviour. This may have been caused by their higher dopamine synthesis capacity (Robinson et al. 2010) or other uncontrolled factors such as the menstrual cycle or contraceptive pill (de Wit et al. 2012). These factors could partly explain gender differences in psychiatric disorders, for example, females are more likely to develop dependence on cocaine following first-time use (O'Brien & Anthony 2005).

The role that dopamine has in the balance between goal-directed and habit systems is complicated. There is dopamine-dependent communication between different regions of the striatum via a cascading loop interconnectivity (Haber et al. 2000). Dysfunction of the dopamine system can interfere with goal-directed and habitual behavioural control. Sensitisation of dopaminergic systems increases activity in the habitual systemand may contribute to compulsive behaviour (Robbins & Everitt 1999, 2005, 2016).

Stress is a likely contributor to the transition from goal-directed to habitual control of action. Stress has direct effects on the rapidly-acting sympathetic nervous system and the slower hypothalamic-pituitary-adrenal axis (Schwabe et al. 2011). In response to stressful situations, there is release of glucocorticoids and catecholamines (Schwabe & Wolf 2011). The concerted action of glucocorticoids and noradrenergic activity on the brain shifted instrumental behaviour from goal-directed to habitual control (Schwabe et al. 2010). Dias-Ferreira et al. (2009) found that stress impairs devaluation sensitivity in rats and postulated that stress might cause compulsive behaviour due to dysfunctional corticostriatal circuitry. They identified atrophy of the prelimbic cortex and dorsomedial striatum with hypertrophy of the dorsolateral striatum following chronic stress. Similar changes have been identified in homologous structures in humans (Soares et al. 2012). Engagement of the habit system following stress might contribute to the development or exacerbation of psychiatric disorders such as drug addiction (Schwabe et al. 2011).

Psychiatric disorders involving compulsive behaviour

Compulsivity is considered to be a quantifiable trans-diagnostic trait caused by an imbalance between goal-directed and habit systems (Gillan et al. 2015), although this imbalance is insufficient to explain compulsive behaviour fully (Everitt & Robbins 2005). Habit formation is not usually a pathological process but can become maladaptive in excess and lead to repetitive, compulsive behaviour. Compulsivity is mediated by a dysfunction in attributing value to outcomes of behaviour (Gillan & Robbins 2014). Persistence of responding despite negative consequences is a feature of many psychiatric disorders including drug and alcohol abuse (Everitt & Robbins 2005), obsessive compulsive disorder (OCD) (Gillan et al. 2011), eating disorders (Voon et al. 2014), Tourette's syndrome (Delorme et al. 2015) and schizophrenia (Morris et al. 2015). These disorders share abnormalities in goal-directed and habit systems. A significant challenge in many studies involving psychiatric disorders is the effect of medication and resolving whether findings are due to the disorder itself or secondary to effects induced by medication to treat the disorder. This can be controlled for in endophenotype studies. Drug addiction, OCD and binge eating disorder are disorders that are primarily characterised by compulsive behaviour.

Drug addiction, including alcoholism

Drug addiction is the endpoint of a series of transitions from voluntary goal-directed drug use through to involuntary, habitual use and ultimately compulsive drug abuse (Everitt & Robbins 2005). Not everyone who uses drugs becomes dependent on them, for example, only around 14% of alcohol users become addicted (Anthony et al. 1994). It has been found that non-dependent siblings of drug-dependent adults possess similar brain structure abnormalities (Ersche et al. 2013). Research into how compulsive drug abuse develops from volitional drug taking might identify neural differences that contribute to a vulnerability to drug addiction. Habitual drug-seeking requires engagement of S-R habit systems because the ultimate goal has been devalued (Everitt & Robbins 2016). Different drugs have shared rewarding, reinforcing effects which strengthen S-R associations (Gillan et al. 2015). Many studies have suggested that the transition from goal-directed control to habitual control of behaviour, paralleled by the shift from associative striatum to sensorimotor striatum, underlies drug-seeking behaviour (Gillan et al. 2015).

The neural transitions and changes in plasticity may be a causeor consequence of chronic self-administration

of toxic drugs (Everitt & Robbins 2005). A pre-existing vulnerability to developing habits could be exacerbated by persistent drug use. Research into the molecular basis of habit formation has shown that long-term changes in plasticity in the striatum and dopaminergic midbrain can be influenced directly by a drug (Gerdeman et al. 2003). Drugs can use synaptic plasticity to modify the functioning of corticostriatal circuits and induce habitual behaviour. This can be achieved in one way by changing medium spiny neuron activity in the striatum (Jog et al. 1999). Secondary changes in microglial activation following drug use have also been shown in methamphetamine-dependent individuals (Sekine et al. 2008). These changes are caused directly by the action of the drug and may further enhance the habitual system.

The development of compulsive drug-seeking is linked to a transition of control from prefrontal cortical to striatal control and from ventral to dorsal striatal control (Everitt & Robbins 2005). Loss of control in alcohol addiction is mirrored by a devolution of control from the dorsomedial striatum to the dorsolateral striatum. Inactivation of the dorsolateral striatum reverses drug-seeking in rats exposed to alcohol (Corbit et al. 2012). Heavy drinkers show higher activation of the dorsal striatum than the ventral striatum following presentation of alcohol-related conditional stimuli (Vollstadt-Klein et al. 2010). There were similar findings in abstinent alcohol-dependent individuals. Sjoerds et al. (2013) found that their knowledge of A-O associations was reduced. This was accompanied by reduced activity of brain areas involved in goal-directed action but increased activity in areas involved in habitual action. Nicotine self-stimulation becomes insensitive to devaluation with extensive training and implicates the dorsolateral striatum and substantia nigra pars compacta, part of the nigrostriatal dopaminergic system (Clemenset al. 2014). The effect of extended training on behaviour has also been demonstrated in cocaine abuse where there is a shift towards habitual drug-seeking (Zapata et al. 2010). Non-contingent amphetamine treatment led to a rapid development of habits that mimicked overtraining (Nelson & Killcross 2006). A vulnerability to drug addiction might be associated with increased putamen volume as this finding was present in both cocaine-dependent individuals and their siblings who were not addicted to drugs (Ersche et al. 2013). Dysfunction in the circuits associated with goal-directed control was found in drug abusers. There is a decrease in the volume of the orbitofrontal cortex in cocaine-dependent individuals (Franklin et al. 2002) and methamphetamine-dependent individuals (Nakama et al. 2011). Lower caudate nucleus volumes are also seen with methamphetamine use (Morales et al. 2012). This is consistent with a study by Furlong et al. (2015) who found reductions in c-Fos-related immunoreactivity in the dorsomedial stratum after exposure to methamphetamine. The greater cognitive effort required by the goal-directed system means that loss of control over fronto-executive functions produces dominance of habitual behaviour through an impairment of the goal-directed system (Robbins & Everitt 1999). These studies contribute to the conceptualisation of addiction as an imbalance between goal-directed and habit systems with impaired goal-directed action and over reliance on S-R habit learning.

Natural rewards such as food can have effects on behaviour that parallel the behaviour evoked by artificial rewards such as drugs (Voon et al. 2014). Food is more sensitive to devaluation than alcohol (Dickinson et al. 2002) but can still reinforce compulsive behaviour in eating disorders. Voon et al. (2014) showed that greater model-free habit formation may underlie repetitive behaviours in binge eating disorder. This is caused by lower caudate nucleus and medial orbito-frontal cortex volumes which are associated with the goal-directed system. In a different study, rats were given restricted access to condensed milk followed by instrumental training for food reward (Furlong et al. 2014). The rats were found to be insensitive to deva-luation which correlated with activity in the dorsolateral striatum. The changes in brain activity in drug addiction are very similar.

Obsessive-compulsive disorder

OCD is a disorder of behavioural inhibition where someone is unable to control their thoughts or feelings which results in repetitive, stereotyped, ritualistic patterns of compulsive behaviour to neutralise their anxiety (Milad & Rauch 2012). Patients with OCD often realise that their compulsive behaviours are not beneficial but they cannot exert self-control. OCD is different to other compulsive disorders in that OCD patientsperform aversive, rather than appetitive, habits to reduce the likelihood of adverse consequences. The reinforcement is the sense of relief from anxiety having performed the behaviour. Avoidance behaviour might be particularly sensitive to habit formation. OCD patients show a lack of sensitivity to the outcome of their habit but preserved sensitivity to broader goals (Gillan et al. 2011). They exhibit behavioural inflexi-bility which can be accounted for by difficulties switching between goal-directed and habit systems (Shenhav et al. 2013).

In OCD, there is dysfunction in the corticostriatal loops that mediate behavioural control, particularly the anterior cingulate cortex implicated in conflict moni-toring and the premotor and supplementary motor areas controlling action selection (Milad & Rauch 2012). The amygdala and several other limbic structures are involved in dysfunctional emotional processing in OCD (Fiddick 2011). Milad and Rauch (2012) suggested that fear extinction is impaired in OCD. This is caused by reduced activation of the ventromedial prefrontal cortex and increased activation of the dorsal anterior cingulate cortex. These areas have a role in fear conditioning along with the amygdala. Remediating the function of

these areas, by increasing activation of the ventromedial prefrontal cortex for example, may strengthen fear extinction and help to reduce OCD symptoms. OCD must be a disorder of maladaptive habit learning because frontostriatal circuits form the neural basis of both OCD and the habit system (Graybiel & Rauch 2000). More recently, Banca et al. (2015) used a live provocation fMRI study to investigate the neural substrates underlying the cognitive bias towards habit formation in OCD. During symptom-provoking conditions, there was hyperactivity of the putaminal regions, caudal cingulate cortex, amygdala, subthalamic nucleus and motor areas, and deactivation of the ventromedial and dorsolateral prefrontal cortex and dorsal caudate nucleus. This is supported by the discovery that OCD patients have increased grey matter volume in the putamen (Radua et al. 2010) and decreased volume in the orbitofrontal cortex (Maia et al. 2008). This suggests that the balance between the goal-directed system and the habit system is shifted towards habit formation to facilitate compulsive automatic behaviours. These findings support the neural basis underlying habit formation with hyperactivity of the habit system and underactivity of the goal-directed system. A different study contradicts this view and found that the tendency of OCD patients to form habits was reliant on a dysfunctional goal-directed system with hyperactivity of the caudate nucleus (Gillan et al. 2015). Hyperactivity of different systems may be either a cause or consequence of the disorder and this is a difficult distinction to make. Habit biases in OCD may be due to dysfunction of the goal-directed system, the habitual system or both. Another suggestion is that the arbitration between the systems might be dysfunctional and lead to the model-based system being inhibited or the model-free system being promoted (Gillan & Robbins 2014). This idea is supported by another computational study which found model-based control in OCD to be diminished (Voon et al. 2014).

In the Fabulous Fruit Game, Gillan et al. (2011) found that OCD patients' over reliance on S-R learning at the expense of A-O learning can be demonstrated by their vulnerability to slips of action. Although the patients could respond appropriately to stimuli, their knowledge of A-O associations and the value of the outcome of their actions was impaired. Another finding in the study was that symptom severity predicted slips of action. Patients with OCD carry out compulsive acts because of a deficit in goal-directed control and a consequent over reliance on habitual control of action. This is comparable to drug addiction where an imbalance in these behavioural systems leads to compulsive behaviours. Many studies investigating goal-directed and habitual control are based on appetitive behaviour but OCD is characterised by avoidance behaviour. One study trained OCD patients and healthy controls to avoid aversive electric shocks by performing a certain response to stimuli (Gillan et al. 2014). This directly tested the behaviour that results in negative reinforcement in OCD. Following initial training, one electrode was removed from their wrist and devalued. The electrode on the other wrist remained connected. OCD patients were found to make more responses to stimuli predicting the devalued shock which would no longer take place. This demonstrates that the habit system in OCD is controlling behaviour in both appetitive and aversive conditions.

Compulsivity is a hallmark of both OCD and drug-addiction. There may be shared abnormalities in brain systems in patients with compulsive disorders. Meunier et al. (2012) compared functional neural connectivity in OCD patients and stimulant-dependent individuals. In both disorders, there was reduced connectivity in the right orbitofrontal cortex, which may be a generic abnormality found in compulsive disorders. Deficits in goal-directed control may be caused by a reduction in top-down control. Looking at compulsivity as a trans-diagnostic trait across diagnostic categories may lead to identification of other abnormalities in goal-directed structures that can be targeted with treatment.

Other psychiatric disorders

Goal-directed and habit systems may be dysfunctional in other neuropsychiatric disorders which are not primarily characterised by compulsive behaviour.

Tourette's syndrome

Tourette's syndrome is characterised by voluntary movements which are performed in an automatic way (Singer 2013). Stereotyped movements in Tourette's syndrome are known as tics and share neural substrates with habits, such as the sensorimotor striatum (Ashby et al. 2010). Delorme et al. (2015) administered an instrumental learning paradigm and found that unmedicated patients with Tourette's syndrome relied on habitual behavioural control which correlated with the severity of the tic. Tourette's syndrome patients had stronger white matter connectivity between the right motor cortex and putamen which form part of the habit system. The increased connectivity might be mediated by dysregulation of striatal and extra-striatal dopamine systems (Segura & Strafella 2013). This suggests that there is enhanced habit formation in Tourette's syndrome rather than a deficit in the goal-directed system. However, smaller caudate nucleus volumes are present in Tourette's syndrome patients (Peterson et al. 1993) which suggests that there may also be a deficit in goal-directed control. Some Tourette's syndrome patients have associated obsessive-compulsive behaviours which might be explained by the overlapping neural bases in OCD and Tourette's syndrome (Leckman et al. 1997). The urge to perform a tic resembles the compulsive urge to perform a particular behaviour in OCD.

Parkinson's disease and frontotemporal dementia

Patients with Parkinson's disease have a deficit of dopamine in the striatum that becomes progressively worse over time (Sharp et al. 2015). In early Parkinson's disease, dopamine depletion is more severe in the

dorsal striatum. The depletion then progresses to other parts of the striatum and the prefrontal cortex later on (Kish et al. 1988). Instrumental learning is deficient in Parkinson's disease, and it was proposed that patients had a specific deficit in S-R habit learning (Knowlton et al. 1996). This supports the theory that model-free behaviour is controlled by a dopaminergic reward prediction error. More recent evidence has contradicted this view. De Wit et al. (2011) investigated the ability of mild Parkinson's disease patients to form S-R associations using an instrumental conflict task. They found that S-R learning was preserved. An outcome devaluation test suggested that, with increasing severity of disease, the deficit might be in goal-directed control. This is in accordance with the studies by Wunderlich et al. (2012) and de Wit et al. (2012), who postulated that model-based learning would be impaired by decreasing dopamine levels. Another study used computational models to investigate whether patients with Parkinson's disease had a dopamine-mediated model-based deficit (Sharp et al. 2015). They found that a model-based deficit was present which was associated with poor working memory and could be restored by dopamine replacement. Dopamine is important in model-free reinforcement learning, but also has a role in model-based learning. Dopamine supports working memory in the prefrontal cortex (Sawaguchi & Rakic 1991) which might explain its contribution to model-based learning. Studying the contribution of dopamine to goal-directed and habitual control in Parkinson's disease is complicated. Dopamine depletion affects different parts of the striatum depending on disease severity, medication status and may affect regions mediating goal-directed and habitual control simultaneously.

Frontotemporal dementia is another neurological disorder that affects goal-directed and habit systems. Frontotemporal dementia patients display stereotypical movements and compulsive behaviours (Mendez et al. 2005). The repetitive behaviours result from damage to the caudate nucleus and frontal lobe, which are key components of the goal-directed system (Ames et al. 1994).

Schizophrenia

There have been deficits in goal-directed behaviour identified in schizophrenia. It was previously thought that goal-directed control in schizophrenia was impaired because of decreased motivation to attain goals (Horan et al. 2006). However, hedonic ratings were reported to be normal (Gard et al. 2007). More recently, Morris et al. (2015) found that people with schizophrenia were unable to integrate causal knowledge about A-O associations with changes in outcome value. There was an associated decrease in activity in the caudate nucleus, part of the corticostriatal circuit, and limbic structures such as the amygdala which has a role in goal-directed control. This reflects a general dissociation between cognitive and affective processes that are seen in schizophrenia (Heerey & Gold 2007).

Attention deficit hyperactivity disorder

There is altered sensitivity to reinforcement in ADHD (Barkley 1997). Motivational impairments in ADHD result from an inability to predict rewarding outcomes and reduced contingency awareness (Griffiths et al. 2014) causing action selection to be poorly controlled. There is dopamine dysfunction in ADHD. Tripp and Wickens (2008) proposed that altered phasic dopamine responses to reward-predictive cues result in reduced A-O associations. Attention negatively correlates with dopamine receptor availability in the nucleus accumbens and caudate nucleus (Volkow et al. 2009). Grey matter reductions also occur in the caudate nucleus which is central to goal-directed control (Castellanos et al. 1994). Individuals with ADHD demonstrate impulsive behaviour where they are unable to prevent an initiated response. This may be caused by less white matter integrity in right orbitofrontal fibre tracts (Griffiths et al. 2014). The differences in neural structure and dopamine functioning suggest a deficient goal-directed system might be present and contribute to behaviours associated with ADHD.

Conclusions

The dominance of habitual behaviour in many psychiatric disorders may be caused by a deficit in a goal-directed system, strengthening of a habit system or both of these processes. This has implications for the transdiagnostic approach to studying psychiatric disorders. Compulsivity is a transdiagnostic dimension caused by an imbalance between the goal-directed and habit system (Gillan et al. 2015). However, this term is not applicable to all psychiatric disorders that have been described, although all have commonalities in symptoms and underlying system dysfunction. It may be more appropriate to use transdiagnostic dimensions such as excessive habitual behaviour or goal-directed deficits. They are general sable across many disorders including those which are not primarily characterised by compulsive behaviour. This would reflect the underlying neurobiological dysfunction. The psychiatric disorders that are characterised by these transdiagnostic dimensions do not necessarily display the same symptoms in the same way but have similar underlying system dysfunction. The differences in clinical manifestation can be explained by other transdiagnostic dimensions or by external environmental factors (Voon et al. 2014).

It is important to have a dimensional rather than categorical approach to treating psychiatric disorders (Insel et al. 2010). Many disorders have overlapping symptoms or neural system dysfunction. Comorbidity is frequently present in psychiatric disorders meaning that the presence of one disorder is associated with a higher probability of having another disorder. This may be explained by common dysfunction in the goal-directed and habit systems. The Diagnostic and Statistical Manual of Mental Disorders (DMS) has traditionally

provided categorical classification of psychiatric disorders. In contrast, the Research Domain Criteria (RDoC) initiative is dimensional, and uses broad neurocognitive dysfunction that may be related to many different psychiatric disorders (Insel et al. 2010). A categorical view of psychiatric disorders is not in agreement with the clinical presentation of psychiatric disorders, which is diverse and dependent on the individual patient's experience. A dimensional view might be seen as going against the idea of individualised medicine, but it incorporates underlying neural bases. It could be used to identify genes associated with system abnormalities that predispose individuals to these disorders.

Habitual thought processes could also be included in the dimensional framework of excessive habitual behaviour or goal-directed deficits. They may prove to be disorders that have goal-directed or habit system dysfunction. Many psychiatric studies use the behavioural manifestation of disorders but there are abnormalities in affective, cognitive and perceptual components. Ruminations predict the onset and maintenance of symptoms in depression (Nolen-Hoeksema 2000). Hertel (2012) proposed that ruminations are a habit of thought because they occur through automatic S-R association and when there is poor cognitive control. Habitual thought processes might account for the persistent nature of delusional beliefs which are strengthened with repetition (Corlett et al. 2009). Like habits.

Treatment of psychiatric disorders based on categorical classifications cannot predict treatment response (Insel et al. 2010). Many psychiatric treatments are not specific to a brain system but act more globally, causing side effects. Research into a treatment that could specifically enhance activity in the goal-directed system or reduce activity in the habit system may reduce side effects and increase compliance. Dysfunction in the habit system is hard to treat because habits are automatic and beyond cognitive control. Psychiatric disorders that are characterised by enhanced habitual behaviour or a deficit in goal-directed control are likely to become more severe and more difficult to treat with time because the S-R association is strengthened with repetition (Gillan et al. 2015).

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Sophie Woodhead carried out all the research and writing.
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