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Understanding and Shifting Drug-Related Decisions: Contributions of Automatic Decision-Making Processes

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Abstract While substance use is common, only a minority of individuals who use drugs or alcohol develop problematic use. An understanding of the factors underlying the transition from substance use to misuse may improve prevention and intervention efforts. A key feature of substance misuse is ongoing decisions to use drugs or alcohol despite escalating negative consequences. Research findings highlight the importance of both relatively automatic, associative cognitive processes and relatively controlled, deliberative, and rational-analytic cognitive processes, for understanding situational decisions to use drugs. In this review, we discuss several cognitive component processes that may contribute to decision-making that promotes substance use and misuse, with a focus on more automatic processes. A growing body of evidence indicates that relative differences in the strength of these component processes can account for individual differences in the transition from substance use to misuse and may offer important avenues for developing novel intervention strategies.

Keywords Attentional bias · Interoception · Implicit cognition · Delayed discounting · Dual-process models · Automatic action tendencies · Approach-avoidance bias · Substance misuse · Valuation · Impulsivity

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Introduction

Approximately 30 % of adults in the USA meet criteria for a lifetime alcohol use disorder [1] and 10 % meet criteria for a lifetime drug use disorder [2]. These substantial prevalence rates, however, represent only a minority of people who report either experimenting with or regularly using substances; most individuals who use alcohol and other drugs do so without developing problematic use [3]. As such, delineating the factors underlying these differing substance use trajectories remains a central issue for both prevention and intervention efforts.

Substance users are faced with the decision to use drugs or alcohol many times throughout their life. A key feature of problematic substance use is the ongoing decision to use drugs or alcohol despite escalating negative consequences. Prevention and intervention strategies often attempt to influence the behavioral choices that individuals make to decrease the likelihood of substance use in these situations. However, the effects of these intervention strategies have generally been modest, and continued substance use remains a frequent outcome [4]. Explicating key components of the decision-making process and how they relate to the narrowing behavioral repertoire commonly seen in problem substance users [5] may enhance our understanding of substance use disorders and guide the development of more effective prevention and intervention strategies.

Recent years have seen increasing interest in the application of dual-process models to the cognitive components underpinning decisions about health-related behaviors. In general, dual-process theories highlight a continuum between two qualitatively different forms of cognitive processing that influence behavior: (1) a relatively automatic, associative, impulsive system which entails the immediate appraisal of stimuli and which may be more difficult to control in the moment and (2) a relatively controlled, rational-analytic system that involves conscious deliberation and reflection [6]. Extension of this model to addictive behaviors has given rise to a theoretical framework that postulates the following: (1) an appetitive, approach-oriented system, characterized by increasing automaticity of drug use in specific environmental contexts and (2) a more reflective and deliberative system that includes symbolic processing, characterized as a controlled regulatory system of limited capacity, which may be weakened in individuals with substance use disorders [7]. The relative strength of each system, and how they interact in given circumstances, is thought to influence decision-making and situation-specific behavioral choices to use drugs [8]. It is important to note that the specific influence of relatively automatic and associative processes on high-order cognitive processes like decision making continues to be debated [9]. Further, the mechanisms by which different components interact and influence conscious deliberation remain an important area of research. However, although the validity of aspects of dual-process theories continues to be debated [6], these models provide a useful heuristic that has yielded a growing empirical literature on the cognitive components of decision making that may contribute to problematic patterns of substance use.

While dual-process models link behavioral choice to two qualitatively different systems, it has also been postulated that numerous neurocognitive processes [10] operate within each system. In this review, we highlight several neurocognitive constructs thought to contribute to the decision making that underlies repeated and/or problematic substance use. We have placed particular emphasis on automatic-, associative-, and impulse-related cognitive processes as they have received less attention in the intervention and prevention literature, and research in these domains may guide the development of novel intervention strategies. We discuss the concepts of the following: (1) interoception; (2) implicit cognition, highlighting attentional bias and automatic action tendencies; and (3) impulsivity. Our focus includes both clinical and nonclinical investigations and where applicable, how research in these domains has informed the development of novel interventions. We conclude with recommendations for future research.

Interoception

Interoception, broadly defined as a sense of the physiological state of the body [11, 12], has rarely been included in considerations of the cognitive components of drug-related decision making, perhaps because the study of interoception in drug abuse remains a relatively new field. Within a dual-process framework, interoception is strongly influenced by automatic processes, with higher-level interoceptive experiences (including both specific physiological sensations and a broader sense of the physical self) emerging in conscious awareness to varying degrees.

Interoception is thought to involve the transfer of peripheral sensory information to the posterior insular cortex (PI) where primary interoceptive information (e.g., temperature and touch) is represented. In humans, primary sensations appear to be integrated into higher-level subjective feelings in the anterior insula (AI), particularly in the right hemisphere [11, 13]. Interoception is believed to serve a homeostatic purpose, alerting the individual when the physiological state of the body is suboptimal, to motivate approach or avoidance behavior aiming to return the individual to homeostatic equilibrium [11, 14]. Within this framework, decision making can be regarded as a component of homeostatic functioning, with actions selected to return the individual to optimal homeostasis (a dynamic state), based on an integration of interoceptive and external information [15]. For example, just as the visceral sensations of hunger motivate decisions to acquire and consume food when it is available in the environment, the visceral sensations of drug craving may motivate decisions to acquire and use drugs. Importantly, such effects may occur with or without conscious awareness. Interoception may thus be a fundamental contributor to decision making, as well as to the motivational and emotional states underlying and influencing choices.

Disrupted interoception could contribute to maladaptive decision making in drug users in several ways; to date, limited research has assessed these relationships. Individuals with drug use disorders could have alterations at the level of the initial peripheral physiological signals, in the primary awareness of these signals, or in the interpretation and integration of interoceptive signals into higher-level subjective awareness [16]. At each of these levels, disruptions could take the form of increased or decreased function.

Since accurate interoception appears to guide adaptive decision making [17], one possibility is that blunted interoception predisposes toward drug abuse. For example, lack of awareness of aversive visceral responses to risk could contribute to risky decision making. Some evidence indicates that problem drug users do have attenuations in interoceptive processing of nondrug stimuli. Compared to nonusers, methamphetamine-dependent polydrug users showed blunted activation in interoception-related brain regions, including AI, in response to pleasant interoceptive stimuli (soft brush strokes), with no difference in subjective pleasantness [18]. Individuals with problematic stimulant (cocaine, amphetamine) use have been found to exhibit lower activity in

anterior cingulate cortex (ACC; thought to contribute to integration of interoceptive signals and orchestration of behavioral responses; see 19) during an aversive interoceptive task (consisting of a period of increased breathing difficulty) compared to both nonusers and past users. Again, no difference was observed in subjective unpleasantness of the task [20]. Methamphetamine-dependent individuals exhibited reduced PI signaling relative to controls during the same aversive interoceptive challenge (i.e., increased breathing difficulty). This was coupled with lower activation in the ACC during negative feedback after decision making under aversive interoceptive challenge. Users were also less able to correct their decision making based on feedback [21]. Together, these findings provide some support for the notion that processing of positive and negative nondrug interoceptive stimuli is blunted in drug abuse, potentially contributing to maladaptive decision making.

Conversely, increased interoceptive processing of conditioned drug-related cues may contribute to drug craving: several functional MRI studies in human substance users have shown increased insula activation to drug cues, insula lesions may reduce urges to smoke cigarettes, and rodent studies indicate that disruption of insula function decreases drug self-administration [22–24]. Acutely, abused drugs themselves produce distinctive physiological changes [25–28] giving rise to powerful, and in many cases enjoyable, visceral sensations [16, 23]. Physiological changes such as sudden shifts in autonomic function contribute to the unique subjective experiences of drugs and are strongly implicated in rewarding drug effects [23].

Higher-level integration of interoceptive signals may depend on expectations regarding the ideal state of the body, generating a "body-prediction error" between the ideal bodily state and one's actual physiological condition, and motivating action aimed at reducing this error signal [29]. Thus, problem drug users could experience a distortion in the perceived ideal bodily state, motivating maladaptive decision making. Indeed, repeated experiences of the positive interoceptive effects of drugs may shift the perceived ideal bodily state, with decisions to use drugs serving the homeostatic function of reducing the bodily error signal and returning the body to the drug intoxicated "ideal" state [23, 29].

Treatment Implications Visceral sensations, and the interoceptive experience of them, thus appear to play important roles in decision making in drug abuse. Little is known, however, about how best to target disrupted interoception in treatment, and whether such interventions would improve overall outcome in drug abuse treatment. Despite limited evidence about interventions targeting interoception, the initial findings described above suggest tentative possibilities. In the first instance, assessment of interoceptive capacities in individuals entering treatment could identify individual vulnerabilities in this domain [16]. Given the role of insula cortex in processing drug-related cues, it has been proposed that this brain region could be targeted using neuromodulatory techniques, although caution would be required in light of the important role of the insula in other dimensions of function [22]. Behavioral options for targeting altered interoception in drug users include mindfulness-based strategies, which may facilitate greater awareness of interoceptive responses to drug-related cues and disrupt habitual associations between craving states and drug-seeking behavior [17]. A small pilot study assessing the feasibility of a mindfulness-based approach and incorporating specific interoceptive training and manual (massage) therapy in women in treatment for substance use disorders suggested that such a program may increase abstinence rates relative to treatment-as-usual [10]. Importantly, mindfulness-based approaches have the potential to address both excessive interoceptive responses to drug cues and blunted responses to nondrug stimuli. A valuable future research direction will thus be to assess the extent to which normalized interoceptive awareness mediates the efficacy of mindfulness-based treatment approaches for drug use disorders.

Implicit Cognition: Overview

Individuals accumulate a range of experiences over their substance use careers. These experiences form the basis of the associations stored in memory between drug use and particular outcomes, influencing the salience of drug-related stimuli, and the extent to which individuals approach or avoid drug stimuli and decide to use drugs. Historically, research assessing these cognitive constructs has employed questionnaires directly asking participants to report on their expectations, attitudes, beliefs, and reasons for using substances. Such assessment methods are termed explicit, or direct, as individuals are aware of what is being asked of them. Explicit assessment allows for use of controlled, conscious, deliberative cognitive processes, as well as providing an opportunity for individuals to craft answers based on social acceptability. It is also unclear whether these methods fully capture the range of cognitive processes influencing decision making; for example, automatic cognitive processes may not be accessible using introspective methods. Given these concerns, there has been growing interest in employing implicit or indirect assessment methods. The term implicit can encompass methods in which individuals (1) are not aware which cognitive processes are being measured, (2) cannot access the cognitive processes being assessed by introspection, and/or (3) cannot control the outcome of the assessment procedure, despite being aware of the process being assessed [30]. Herein, we focus on those measures that incorporate drug-related stimuli or content, though nondrug-related tasks have also been employed to investigate implicit functions in substance abusers [31].

In addiction research, the term implicit most often characterizes assessments (e.g., of attentional bias) that do not ask individuals to directly report on their beliefs [32, 33]. Implicit cognitive assessment procedures include computerized tasks requiring individuals to relate or categorize stimuli (e.g., Implicit Relational Assessment Procedure, Implicit Association Test), manipulate computer controls that stimulate movement toward or away from a substance-related stimulus (e.g., approach/avoidance task), or generate semantic associations (e.g., word association). These tasks have been applied in three important domains in the addiction field: attentional processes, automatically activated approach and avoidance tendencies, and memory associations between substance use and positive and negative outcomes.

From a dual-process perspective, implicit assessments may capture the automatic/associative responses to drug-related cues, facilitate the study of how automatic/associative responses interact with more reflective and controlled cognitive processes in the context of making decisions, and may also help identify key cognitive targets for novel interventions [34, 35]. Several reviews support the importance of implicit assessment procedures for understanding substance use (e.g., 36), in that they may differentiate groups of substance users (e.g., social versus problem drinkers) and account for the variability in severity of substance use within groups (i.e., variation in drinking among heavy drinkers). Importantly, implicit measures account for interindividual differences over and above contributions of explicit measures (e.g., questionnaires), supporting their capacity to capture cognitive processes not assessed using traditional methods.

Roefs et al. [35] provide a detailed qualitative review that captures many of the methodological intricacies of assessing implicit cognition in alcohol, nicotine, cannabis, and cocaine users. Their review indicates that drinkers have both implicit positive and negative associations to alcohol, with the positive associations being more predictive of alcohol use. Similarly, cigarette smokers are more likely to demonstrate implicit positive associations with cigarette-related stimuli, which predict higher self-reported smoking levels, craving, and difficulty abstaining. Relationships between implicit measures and cannabis and cocaine use were less robust. However, Roefs et al. [35] did not include studies of attentional bias or semantic memory. Rooke et al. [37], investigating a wider range of implicit processes (attentional bias, semantic memory, and attitudes), demonstrated a moderately strong positive association between measures of implicit cognition and substance use across different age groups (adult versus adolescent), types of substances (e.g., alcohol, cigarettes, marijuana), cognitive process (e.g., arousal, attention, semantic memory), and implicit assessment methods (e.g., Implicit Assessment Procedure; Word Association Task).

Together, a growing body of evidence suggests that the assessment of automatic cognitive processes can account for clinically relevant differences in substance use and may exert an important effect across the broader developmental trajectory of substance use, misuse, and disorder. Further, several reviews and commentaries have highlighted the role of implicit cognition research in informing intervention and prevention strategies [32, 38•]. This avenue of investigation, although fairly young in the substance use domain, has yielded encouraging findings in the areas of attentional bias and automatic action tendencies. Thus, we highlight research addressing these two implicit cognitive processes below (see Wiers et al. [38•, 39•] for more discussion of evaluative memory bias modification procedures).

Attentional Bias[1]

Substance-related attentional bias refers to the disproportionate diversion of an individual's attention toward substance-related stimuli and experiences, such as substance paraphernalia and fellow users [39•]. In the laboratory, this is typically measured by tasks (e.g., Drug Stroop task) that employ representations of these stimuli (e.g., written words) and require the participant to quickly identify some feature of the stimuli (e.g., font color). Attentional bias is indexed by the difference in reaction times to the substance-associated stimuli versus the control stimuli, with greater times reflecting increased attentional bias to the substance-associated stimuli.

Drug-related stimuli are thought to acquire their salience by means of classical conditioning over time, and the resultant orienting and lingering of attention on these stimuli or their representations appears to occur outside of conscious awareness. Thus, within a dual-process framework, attentional bias is classified as an automatic/associative phenomenon. Greater attentional bias toward substance-related stimuli (which signify the potential availability of substances) could trigger a decision to seek out the substance and make it more difficult for the reflective system to engage and inhibit such a decision.

Studies have consistently found that experienced substance users demonstrate attentional bias toward stimuli associated with their primary substance (including nicotine, alcohol, marijuana, cocaine, and heroin), as measured by Drug Stroop tasks [41]. Moreover, substance-related attentional bias has specificity: on average, nonsubstance-using individuals do not exhibit it, and primary users of particular substances do not exhibit it toward stimuli from other substance classes [42]. Attentional bias also seems to be concurrently associated with relevant clinical characteristics, such as drug craving [41], impulsivity [43], and reported level of substance use [44]. Correspondingly, attentional bias is associated with activity in dopamine (DA)-rich brain regions that subserve reward processing and cognitive control, such as the nucleus

[1] The reader is referred to a special issue of CNS Spectrums (2014, 40) that covers many of these points on attentional bias in greater depth.

accumbens (NAcc), orbitofrontal cortex (OFC), and anterior cingulate (ACC) [44, 45].

Recent studies (e.g., 46) have replicated earlier findings that attentional bias predicts subsequent clinical outcome in behavioral and pharmacological drug treatment, although the specific treatment modality and the direction of the association may vary between studies. Investigators [44] have also suggested that attentional bias has potential as a tool in clinical practice to distinguish between subtypes of substance users (e.g., dependent vs recreational users), bypassing reliance on patient self-report. This could potentially be a useful tool with relatively easy implementation, and more investigation needs to be done to determine whether attentional bias can reliably index clinical severity.

Treatment Implications Based on the findings reviewed above, investigators have been developing cognitive-behavioral therapies to modify attentional bias. Attentional retraining is a cognitive control method designed to assist substance users in overcoming attentional bias by means of initial assessment of drug-related attentional bias severity, repeated goal-setting on the desired level of reduction in attentional bias, practice on redirecting attention from the computerized drug-related stimuli, and feedback on performance [47]. Initial reports [48, 49] indicate that attentional retraining is effective in reducing attentional bias in alcohol abusers but are inconsistent on whether effects generalize to reductions in actual drinking behavior (i.e., decisions to drink). Thus, these results parallel those seen in other cognitive remediation approaches for substance abusers [50]. An interesting extension of these lab-based procedures is the use of mobile devices to export attentional retraining to the natural environment [39•]. Further research is needed to convincingly demonstrate the effectiveness of these and clinic-based attentional retraining procedures for alcohol and other substances. Pharmacological manipulations of attentional bias, primarily targeting the DA system, have also been tested in substance users in the laboratory [40]. Results of the limited number of preliminary studies have been mixed, with no consistent target emerging for clinical testing.

Automatic Approach and Avoidance Tendencies

In addition to attentional bias, which is framed as a precursor to substance-related behavior, there has been substantial interest in assessing the extent to which substance users develop a bias to *approach* drug-related cues over the course of their substance use careers [51]. From this perspective, it is hypothesized that individuals not only develop increased attention for stimuli that are highly reinforcing, they also develop a tendency to approach such stimuli via an activated motivational state [52]. Similar to attentional bias, strong approach tendencies may make it more difficult for an individual to invoke the deliberative cognitive processes that would facilitate the decision to engage in alternative behaviors in situations previously associated with drug and alcohol use.

Two types of computer-based assessments have been employed in automatic action tendency studies. In the first (Stimulus-Response Compatibility Task; SRC), participants are explicitly instructed to move a figure (i.e., mannequin) toward or away from drug-related and neutral stimuli. Approach and avoidance biases are quantified by differences in the times to move the figure toward or away from drug-related, versus nondrug-related stimuli, respectively. For example, an approach bias indicates that the difference between moving toward drug stimuli compared to nondrug stimuli was larger than the time difference between moving away from drug stimuli relative to nondrug stimuli. Alternatively, Wiers and colleagues developed a computerized task to capture relatively more automatic approach-avoidance tendencies (Approach-Avoidance Task; AAT). A key component of the AAT is that participants are asked to respond (pull or push a joy stick) to stimuli based on the format of a picture (e.g., landscape vs portrait; or rotated to the left vs the right) not the content (e.g., pictures of alcohol or the control stimuli). This instructional set (attending to format rather than content) designates the AAT as an implicit measure, because differences in approach-avoidance response times between substance-related pictures and nonsubstance stimuli are not based on an effortful evaluation of the content. Thus, reliable differences are hypothesized to reflect a more automatic, indirect evaluation of the stimulus.

Studies employing the SRC task have demonstrated approach biases among abstinent heroin abusers [53], nicotine-dependent individuals [54], heavy drinkers [55], and cannabis-dependent participants [56], compared to control groups. In contrast, heavy cannabis users showed no differences in approach or avoidance responses compared to controls in a study investigating the neural correlates of approach bias [57]. However, among the cannabis users, stronger neural activation (measured with functional magnetic resonance imaging; fMRI) in the dorsolateral prefrontal cortex (dlPFC) and the anterior cingulate cortex (ACC) during cannabis approach relative to cannabis avoidance trials was associated with fewer cannabis problems at follow-up. Importantly, DLPFC and ACC have been implicated in decision-making processes including self-regulation and cognitive control [58, 59]. Thus, the findings of Cousijn et al. [57] suggest that reduced brain activation in regions that subserve reflective and self-regulatory cognitive process, while performing an approach bias task, is predictive of more severe drug problems among active cannabis users. Together, these studies support the presence of a drug-related approach bias among substance users relative to nonusers and are consistent with a dual-process framework postulating a potentially important interplay between performance on implicit cognitive tasks and more

deliberative cognitive processes. However, the extent to which these studies fully capture implicit processes based on the instructional set has been questioned [60].

Studies employing the AAT have demonstrated automatic approach biases in both clinical and nonclinical populations. Among young adult social drinkers, individuals reporting relatively higher levels of alcohol consumption and problems demonstrated a greater approach bias toward alcohol stimuli than those reporting lower levels of alcohol use [61]. Similarly, among adolescent drinkers, greater reported alcohol use was associated with a stronger approach bias [62]. An automatic approach bias has also been demonstrated among a more homogenous group of heavy drinking adults [63], relative to controls.

When compared to nondependent drinkers, drinkers with alcohol dependence have a stronger approach bias toward alcohol cues, which was associated with greater activity in the nucleus accumbens (NAcc) and medial prefrontal cortex (mPFC) during task performance [64]. These brain regions are associated with other component processes of decision making, including reward prediction learning and valuation processes. Similar findings have been demonstrated among heavy cannabis users compared to noncannabis using controls, although these are inconsistent with the study described above that employed the SRC task. Cannabis users demonstrated a stronger approach bias to cannabis stimuli and this bias correlated with weekly cannabis use at a 6-month follow-up [57].

Dual-process theories hypothesize that the relative strengths of the two systems and how their components interact influence the situational behavioral choice to engage in substance use. Several studies have investigated the relationship between automatic approach tendencies and explicit cognitive functions, for example, working memory. Working memory capacity was not found to moderate the strength of alcohol approach tendencies [65] or their relationship with alcohol use [66] among adolescents. However, a methodologically stronger study did find a moderating effect of working memory such that young adult problem drinkers with lower working memory evidenced the greatest approach action tendency [67]. Further, response inhibition as assessed with a classic Stroop task did not moderate the relationship between a cannabis approach bias and cannabis use among active cannabis smokers [68]. However, among at risk adolescent drinkers, automatic alcohol approach biases predicted future alcohol use only among individuals demonstrating weaker response inhibition [62].

In a study suggesting that automatic approach biases among adolescents may be mitigated in contexts in which negative consequences are more likely to be factored into the decision-making processes, Pieters et al. [65] demonstrated a significant relationship between automatic approach tendencies and self-reported alcohol use. Importantly, stronger action tendencies were associated with greater alcohol use only among adolescents whose parents were perceived as being more permissive of alcohol use; approach tendencies were associated with less alcohol use among male adolescents with strict parents. Together, these mixed results suggest that cognitive factors associated with a more deliberate cognitive processing system may influence how automatic approach-avoidance tendencies relate to substance use; however, this relationship depends in part on how the approach biases are assessed as well as which controlled cognitive components are under consideration.

Treatment Implications An important component to the automatic approach literature is the implications of this research for developing novel prevention and intervention strategies. From a dual-process perspective, strategies can be developed to either alter the strength of automatic approach-avoidance tendencies or to facilitate the development and utilization of more deliberate cognitive control processes. A causal role of automatic approach-avoidance tendencies in substance use was supported in a study in which training an alcohol-approach bias increased alcohol consumption among heavy alcohol users who were not treatment seeking [69]. Similar findings were also evidenced among college drinkers reporting heavy alcohol use [67]. Together, these findings indicate that manipulating approach biases may be an important way to influence drinking behavior.

Accordingly, findings across clinical populations support the idea that directly manipulating automatic approach and avoidance biases may offer a complementary intervention strategy. For example, Eberl et al. [70] randomized 475 alcohol-dependent patients enrolled in an inpatient treatment program to one of two training conditions: avoidance training and no training. The AAT procedure was utilized as a training platform and the intervention involved 12 training sessions over 6 weeks. Patients in avoidance training were taught to respond to alcohol-related pictures with an avoidance move (push the joystick) and to nonalcohol pictures with an approach move (pull the joystick). Although no approach bias was demonstrated before training, patients in the training group showed a stronger alcohol-avoidance bias following training. Importantly, at a 1-year follow-up, 51 % of patients in the training condition were categorized as being successful compared to 43 % in the no-training group. Similar effects of training on drinking behavior have been demonstrated in other clinical samples [71]. These findings suggest that the direct training of automatic action tendencies can impact drinking behavior by either decreasing the strength of an approach bias and/or strengthening an automatic avoidance bias. In turn, the relative alteration of approach-avoidance biases may be the opportunity for a more deliberative decisional process to guide behavior. Thus, including computerized implicit training procedures may increase the overall efficacy of more traditional counseling approaches.

Impulsivity

In the substance use field, impulsivity has received perhaps the broadest attention of the cognitive components of decision making. Impulsivity is a multifaceted construct that can construed as a psychological state or trait and can be measured by cognitive tasks (e.g., Balloon Analogue Risk Task; 72) or self-report questionnaires (e.g., Behavioral Impulsivity Scale; 73). Impulsivity as measured by these two methodologies does not covary within individuals, suggesting that these methods may be capturing different phenomena [74]. Impulsivity, measured by task performance or self-report, can be further subdivided into component functions such as cognitive/motor disinhibition, temporal discounting, and risk-taking [75], among others. Within a dual-process framework, regardless of definition or level of analysis, impulsivity can be seen [75] as a failure of deliberative (i.e., "top-down" or executive) functions to control automatic/associative processes (e.g., "bottom-up" or reward-seeking and habits).

The literature generally documents that across a host of measurement types, substance users exhibit greater levels of impulsivity relative to healthy controls [76–78].[2]. For example, compared to controls, cocaine abusers have greater (1) difficulty inhibiting primed motor responses on a stop-signal task, i.e., response disinhibition [82]; (2) preference for immediate (hypothetical) rewards over larger, delayed ones, i.e., delay discounting [83], (3) preference for relatively immediate and large rewards that also confer a risk for large losses, i.e., risk-taking [84]; and (4) frequency of self-reported risky and sensation-seeking behaviors, in addition to substance use, in the natural environment [85].

With some variation, similar findings have been reported for abusers of other substances, such as alcohol [86, 87]. An interesting study [80•] found that while dependent cocaine users exhibited steeper delay discounting rates for hypothetical rewards than noncocaine users, recreational cocaine users did not. One interpretation of this data is that relatively steeper discounting may be associated with the transition from substance use to misuse, though the cross-sectional design of the study limits the definitiveness of this conclusion.

As noted above, impulsivity is associated with attentional bias for substance-related stimuli and is hypothesized to facilitate the formation of such biases in substance users [86]. Impulsivity appears to be mediated by brain dopamine (DA) function; specifically, low levels of D2 receptor availability and dopamine signaling are associated with increased impulsivity [88]. Consistent with this, pharmacological studies have found that agents that increase dopamine transmission decrease impulsivity while those that reduce dopamine transmission increase it, although results are mixed and also implicate other neurotransmitters [76, 89].

Treatment Implications Impulsivity may also hinder responses to substance use treatment, as greater impulsivity at treatment baseline is associated with less abstinence during treatment across a range of modalities and substance use populations [75]. These authors further hypothesized that established behavioral interventions may exert effects on substance abuse in part through reducing impulsivity, with verbally based treatments such as relapse prevention therapy (RPT) and mindfulness training strengthening deliberative functions [90] and operant treatments such as contingency management (CM) decreasing the influence of automatic/associative functions [91]. In support of this idea, in a laboratory study [79], we found that a real (as opposed to hypothetical) monetary contingency reduced risky choices on a gambling task in cocaine-dependent individuals. Further, changes in delay discounting have been demonstrated among substance abuse patients who were successful in drug treatment studies such that better treatment response was associated with a decrease in discounting rates.

Of particular interest has been the relationship between working memory training (WMT) and rate of delayed discounting. Studies have supported WMT as a potential method for improving the function of relevant brain regions in substance abusers, with the aims of decreasing the rate of temporal discounting, strengthening other executive functions, and reducing substance use. Further, several lines of research have documented the effect of computerized training programs on enhancing working memory performance [92]. These findings further highlight an important interplay between component processes and suggest that delay discounting may capture an important dimension of impulsive tendencies that is responsive to both computerized cognitive training procedures and more traditional behavioral interventions [93•].

Conclusion and Future Directions

The overview presented above demonstrates that the cognitive component processes that may contribute to the development

[2] It should be noted that a methodological characteristic that varies across studies of impulsivity but was beyond the scope of this review to explore, is the tangibility of the task rewards (i.e., hypothetical or real). Burgeoning evidence indicates that the performance of substance users on impulsivity tasks, and the associated neural response differs along this axis (e.g., 79. Vadhan NP, Hart CL, Haney M, van Gorp WG, Foltin RW. Decision-making in long-term cocaine users: Effects of a cash monetary contingency on Gambling task performance. Drug and alcohol dependence. 2009;102(1–3):95–101. 80•. Hulka LM, Eisenegger C, Preller KH, Vonmoos M, Jenni D, Bendrick K, et al. Altered social and nonsocial decision making in recreational and dependent cocaine users. Psychological medicine. 2014;44(5):1015–28, 81. Chung T, Geier C, Luna B, Pajtek S, Terwilliger R, Thatcher D, et al. Enhancing response inhibition by incentive: comparison of adolescents with and without substance use disorder. Drug and alcohol dependence. 2011;115(1–2):43–50.). It remains to be seen whether ecological validity and clinical relevance also differ in a similar fashion.

of dysregulated decision making in drug abusers, and hence to problematic drug use, are complex and multifaceted. Moreover, there are other candidate neurobehavioral processes that have yet to be evaluated in this context.

One area of interest emerging from the cognitive neuroscience and neuroconomics literature is valuation, the process through which an individual attributes values to competing options in a given decision. Many decisions call for comparison of differing options, which may or may not naturally occur on the same scale [94]. For instance, a direct comparison between receiving $5 and $10 is clear, whereas deciding between $10 and a bag of marijuana requires assessment of the value of each to the decider. Moreover, this value may change depending on numerous factors, such as the time of day, the social environment, competing demands, and the physiological state of the individual (see 95). For example, a bag of heroin will likely hold a different subjective value for a heroin-dependent individual who has recently used than for the same individual in withdrawal. fMRI studies have consistently shown that a region of ventromedial prefrontal cortex (vmPFC) parametrically tracks subjective value across a range of different types of decisions [96, 97]. Moreover, "self-control" appears to involve downregulation (i.e., decreasing) of value signals by brain regions implicated in higher-level cognitive control (e.g., dlPFC; 98). Valuation may thus involve both more automatic (or "bottom-up") processes and modulation by higher-level ("top-down") reflective processes. Given the observation that development of problem drug use is associated with an *overvaluation* of drugs coupled with a *devaluation* of natural reinforcers such as social relationships [99], one can speculate that the neural processes underlying valuation may be disrupted in individuals with drug use disorders. This possibility has not yet, to our knowledge, been systematically investigated.

Another area requiring substantial future research is the extent to which vulnerabilities in component processes of decision making predispose toward the development of drug use disorders, or are causally affected by repeated experiences of drug use (i.e., via neuroadaptions related to pharmacologically distinct drug effects or more generalized processes associated with the development of addiction). Given that the majority of research in humans is cross-sectional, little is known about the etiology or directionality of these relationships. A better understanding of causality in this field would have important implications in terms of improving preventative interventions. Despite this gap in knowledge, it remains clear that many of the cognitive component processes described above may substantially impact treatment outcomes in individuals who have already developed problematic patterns of substance use, and thus are valid targets for intervention regardless of etiology.

Together, the findings described above suggest that disrupted decision making in problematic drug users involves a dynamic interaction between more automatic processes, including those involved in interoception, attentional bias, automatic approach tendencies, and components of impulsivity such as motor disinhibition, with higher-level, more deliberative cognitive control processes. Initial work suggests that visceral sensations, and the interoceptive experience of them, appear to play important roles in maladaptive decision making in drug abusers. Further research is required to elucidate specifically how interoceptive processes may be biased, how these biases guide drug-related decision making, and whether interventions designed to normalize interoception could prove beneficial [17], in individuals with drug use disorders.

Substance-associated attentional bias is a reliable, specific, and clinically relevant phenomenon that may be remediated by cognitive training, although further research is needed to establish its utility as a cognitive marker of substance use severity and mechanism of behavior change, as well as its sensitivity to pharmacological manipulation. Substance-related automatic approach-avoidance biases can differentiate between substance users and nonsubstance users, account for individual differences in alcohol and cannabis use, and may directly impact alcohol consumption. Furthermore, procedures that specifically target approach and avoidance biases have shown promise for enhancing the efficacy of standard drug counseling interventions and more deliberate higher-order cognitive processes appear to influence the relationship between this implicit cognitive process and substance use. Continued research is needed to understand how more deliberate cognitive processes can interact with automatic approach biases to impact decisions to engage in substance use.

Impulsivity is a multidimensional construct that has played a prominent role in substance use theory and research. Across measurement approaches and populations, impulsivity is elevated in substance users relative to nonusers. Moreover, impulsivity may represent a mechanism for the transition from substance use to misuse and is prospectively and longitudinally associated with treatment outcome. Cognitive training procedures and behavioral interventions can impact the relationship between specific dimensions of impulsivity and treatment response. These findings have important implications for guiding the development of cognitive-behavioral interventions.

Developing interventions based on this research that are capable of decreasing the impact of more automatic processes, while enhancing cognitive control capacities, represents a substantial ongoing challenge. More research is needed to further delineate how the component processes that operate on these two levels interact and function during conscious deliberation, and how such deliberation influences behavioral choices. Collectively, these research findings offer the prospect of a more integrated model of decision making in substance use and misuse that may lead to the development of more effective treatment strategies in the future.

Compliance with Ethics Guidelines

Conflict of Interest Kenneth M. Carpenter, Gillinder Bedi, and Nehal P. Vadhan declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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