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**Time perception and impulsivity:
a proposed relationship in addictive disorders**

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Abstract

Addictive disorders are characterized by impulsive behavior that leads to difficulties in preventing certain behaviors despite negative consequences. This symptom predisposes to a vulnerability in developing addictive disorders and is also aggravated by the addiction process itself. As such, understanding the underlying mechanisms of impulsivity is a challenge for understanding the pathophysiology of addiction. One common link between impulsivity and addiction is that both involve actions and decisions that are realized faster than they should be in time. Impulsive traits increase the tendency to choose immediate gratification instead of delayed gratification even when preferred. This observation suggests a relationship between impulsivity and time processing. To better understand this relationship, we reviewed the literature that describes the relationship between time processing and impulsivity in addictive disorders in humans. Despite a lack of literature concerning this question in alcohol, cannabis and gambling disorders, we highlight that addictive behaviors are a good model for understanding the pathophysiology of impulsivity, and could help us to better understand the relationship between time perception and impulsivity.

Keywords: time processing, impulsivity, addictive disorders, cognition.

1. Introduction

Addictive disorders are characterized by a loss of control over goal-directed behaviors towards reward or relief, with problematic substance use and in some case problematic behavior. The loss of control, or compulsivity, is characterized by difficulty to prevent certain behavior/ substance use despite negative consequences, and thus represents a major symptom of the persistence of addictive behaviors. In humans as in animals, the onset of compulsivity is driven by impulsivity traits (Dalley et al., 2011). Impulsivity is defined as a tendency to respond rapidly, without planning and without considering the future consequences of such behavior (Moeller et al., 2001). Individuals with high impulsivity, as in ADHD (Crunelle et al., 2013; Toplak et al., 2003), have a higher risk to develop a substance use disorder or a behavioral addiction. Animal models suggest that impulsivity is associated with certain neurological circuits and neurobiological dysfunction. For example, rats with high impulsivity traits have an increased risk of developing addiction to cocaine, heroin, alcohol, and cannabis (Dalley et al., 2011). Moreover, taking drugs may result in behavioral changes that include impulsivity, as a consequence of the drugs' pharmacological or "neurotoxic" actions in the brain, contributing to the persistence of addictive disorders (Lalanne et al., 2016; Bates et al., 2013). Impulsivity is also associated with an increased risk of relapse in patients who suffer from addiction and who decide to stop their use (Noël et al., 2001; Pitel et al., 2008; 2009). In this way, understanding the pathophysiology of impulsivity is a challenge for understanding the pathophysiology of addictive disorders themselves and their treatment.

1.1 Impulsivity has multiple facets

Impulsivity is generally described as the tendency to commit an inappropriate behavior, often entailing unplanned consequences. In 1965 Ernest Barratt proposed three independent subcategories of impulsivity: motor impulsivity, cognitive impulsivity, and impulsivity related to the difficulty of planning. These factors correspond respectively to the incapacity to inhibit a behavioral response, to the incapacity to take reflective decision in demanding situations, and finally to acting without preliminary reflection for consequences. Barratt's work resulted in one of the most widely used scales of self-assessment regarding impulsivity (Barratt Impulsivity Scale; BIS) (Stanford et al., 2009). In 1999, Evenden proposed that impulsivity has multiple facets and is influenced by several factors such as psychiatric comorbidities, personality disorders and psychoactive drugs. In his review, he argued that human and animal studies showed that different neurochemical bases are involved in impulsive behaviours. In this way, he proposed that impulsivity is not only related to an underactivity of serotonergic neurotransmission, but would also reflect the alteration of different neurobiological pathways with different behavioural expressions. In the same way, subsequent studies (Caswell et al., 2015; Whiteside and Lynam, 2001; Cyders and Coskunpinar, 2011; Smith et al., 2007) revealed that the results obtained through the assessment with the BIS did not systematically correspond to the results obtained by means of various behavioral tasks. Besides, although Caswell et al. (2015) recognized that impulsivity is comprised by several subcategories, they also pointed out that there is no task that explored the different characteristics of the impulsivity together. Caswell et al. distinguish three types of impulsivity: 'motor'-impulsivity (MI), as a failure to inhibit a behavioural response (also termed inhibitory control), and temporal-impulsivity ([TI], also referred to as delay discounting, as the failure to delay gratification). A third subtype is

'reflection'-impulsivity (RI), i.e. the tendency to make decisions without gathering or evaluating necessary information.

Numerous conceptualizations and measurements of impulsivity have resulted in the inconsistent use of the term impulsivity, and have produced varying results regarding the link between impulsivity and risky behaviors. **One common link is that thinking, deciding, reasoning, acting, i.e. all cognitive behaviours, are realized in time. In the case of time acceleration or distortion, all these processes would be degraded which could lead to making premature decisions, without any constructive reasoning, and to impulsive actions without any inhibition. This observation suggests a relationship between impulsivity and temporal processes, and the explicit perception of time.**

1.2 Impulsivity and time processing

While time processing is relevant to impulsivity, which is marked by disordered ability to delay gratification in time, it is not always well identified or discussed. The relationship between time and impulsivity thus remains under-explored and undefined, even though both are implicated in psychiatric disorders including addictive disorders.

In order to understand how time is processed and perceived, it is important to consider the existing cognitive model of time processing. To functionally operationalize the perception of the time flow, Treisman evoked the model of an internal clock in 1963 which measures duration with a pacemaker and an accumulator unit. The pacemaker emits signals, or pulses, during a given interval, which are read and counted by the accumulator. The number of pulses counted during that interval then represents its duration. Variations of this basic pacemaker-accumulator clock have been devised, which all build upon this internal clock model (Gibbon et al., 1984; Wearden, 2017; Zakay & Block, 1997).

The perception of time remains closely linked to our emotional states, which either dilate or contract subjective duration depending on levels of arousal and allocation of attention. Accordingly, subjective time will seem longer or shorter in relation to objective time (Moreira et al., 2016; Wittmann and Paulus, 2007).

To account for the changes in time perception due to variations in subjective emotional states, the attentional gate was added to the internal clock in the study of human time processing; pulses are only registered when attention is directed to time and a switch closes, thus opening the gate from pacemaker to accumulator and allowing pulses to be counted and read (see Fig 1). There are two possibilities for how subjective time is influenced: (a) increased attention to time leads to an increased accumulation of pulses; (b) increased arousal levels lead to higher pacemaker rate which in turn leads to a greater accumulation of pulses during a given time interval (Droit-Volet & Meck, 2007; Wittmann & Paulus, 2008) (see Fig 1).

The impact of impulsivity on time perception could explain why impulsive people show a well-established preference for immediate rewards over a delayed but more preferable reward (Wittmann and Paulus, 2007). This phenomenon is known as “delay discounting,” which we can translate as a devaluation of a reward as time elapses, suggesting that reward and time will affect the ability to wait for gratification in opposite ways. Delay discounting refers to the universal human tendency to choose more immediate rewards, a preference that is more dominant in impulsive subjects.

Impulsive individuals are more likely to focus on the passage of time and feel trapped in time when they cannot act on their urges, which could result in longer duration estimates and feeling a slower passage of time. The subsequent overestimation of duration and the feeling

of having to wait too long could lead to making choices based on short-term outcomes instead of long-term consequences.

It has been shown that healthy people who are more impulsive have a faster cognitive tempo than normal, and feel a slower passing of time. This was demonstrated by tasks that measure time interval production and reproduction (Lawrence & Stanford, 1998). Impulsive symptoms are found in neurological disorders, such as in patients with orbito-frontal damage to the brain, whose high impulsivity levels are accompanied by overestimation of time intervals in the minutes' range, (Berlin et al., 2004) and in psychiatric disorders like ADHD (Gonzales-Garrido et al., 2008), as well as in addictive disorders (Aleksandrov, 2005; Atakan et al., on 2012; Cappon & Tyndel, 1967; Rau et al., 2006; Wittmann et al., 2007) (Fig 1).

<Insert Colored Figure 1>

Overall, both the literature and conceptual framework show a relationship between altered time processing and impulsivity, and between impulsivity and addictive disorders. This suggests a link between time, addiction and impulsivity.

In this work, we review the literature that explores the relationship between subjective time and impulsivity in addictive disorders and we discuss the principal results of this review, before proposing new perspectives and hypotheses.

The addictive disorders discussed are those recognized by the DSM-5; alcohol, tobacco, opioid, stimulant, and cannabis use disorders, and gambling disorder. Gambling disorder is included along with substance use disorders because it is recognized by the DSM-5, and also involves an addictive process.

2. Tasks to investigate time and impulsivity in addictive disorders

2.1 Paradigms to investigate impulsivity As impulsivity has been defined as a multifaceted construct, a variety of tasks exist to measure impulsivity, or subcomponents of impulsivity in human subjects. We will consider investigations that use many different methodologies to examine impulsivity, in order to accurately synthesize the existing literature.

Many paradigms are grouped under the term behavioral impulsivity, and include tasks that involve response inhibition (Dougherty et al., 2005). The Go-Stop Impulsivity Paradigm and the Stop-Signal Task assess the capacity to inhibit an initiated response. Subjects must only respond to one specific stimulus and inhibit a response if the stimulus is, for example, presented in the wrong color or wrong order (Dougherty et al., 2005). The Immediate Memory Task (IMT) measures initiation aspects of impulsivity, measured through impulsive error responding (Dougherty et al. 2013). Participants must detect if two sequential stimuli sets are identical, and errors are interpreted as failure to inhibit a response and as increased initiation impulsivity. However, these tasks do not allow examining the effect of delay/time accumulation on impulsivity.

Delay discounting tasks have long been used to capture impulsivity by measuring the extent to which a subject prioritizes the immediacy of a reward in relation to the nature or value of the reward. Such tasks are usually hypothetical monetary reward paradigms, in which a computer program, interlocutor, or questionnaire asks subjects to choose between two rewards of different amounts and at different time delays. Both reward and delay quantities are successively changed in order to measure a subject's subjective threshold for valuing the time delay vs. monetary gain (Reynolds, 2006; Wittmann et al., 2007; Bickel et al., 2012; Koffarnus et al., 2013). For example, in a series of trials a subject may be offered the hypothetical choice between \$500 tomorrow or \$600 in one week, then \$400 tomorrow or

\$600 in a week, etc. (time delays can range from hours to years). Real monetary rewards are also used, asking subjects to decide between an immediate or delayed but higher reward, which is later paid to the subject. In other delay discounting paradigms, money is immediately dispensed from a coin machine as the task progresses (Johnson, 2012) (Figure 2).

Card tasks are also used to assess delay discounting, like the Iowa Gambling Task, by asking subjects to choose between two unknown decks; one deck contains immediate but lower rewards, and the other one offers higher rewards with delays (Petry et al., 1998; Takahashi et al, 2009). In all delay discounting tasks, the role of time is relevant; a certain delay is experienced as a cost that has to be weighed against the reward value. As delay discounting tasks by their nature require subjects to compare and conceptualize hypothetical time delays that are more or less rewarded, it follows that the dimension of time is present in these tests, which are also referred to as intertemporal decision-making tasks (Takahashi, 2006).

<Insert Colored Figure 2>

2.2 Paradigms to investigate time perception

Time perception is investigated with tasks that measure how subjects estimate duration, produce or reproduce time intervals, prepare actions in time, and orientate behavior in time. Experimental paradigms that ask subjects to estimate duration or to produce a time interval assess how factors like arousal and attention affect the hypothesized cognitive timing system. Tasks assessing preparation in time and orientation in time address the larger perspective of how time perception is integrated in behavior. We have included studies that

use these distinct methods and approaches in order to capture a broad range of results that reflect the current domain of time perception research.

In computerized duration processing tasks, participants are often given a time interval indicated with an auditory or visual marker, and then asked to estimate or reproduce the interval with a button press (Davidson & House, 1978; Aleksandrov, 2005; Ulbrich et al., 2007; Gonzalez-Garrido et al., 2008; Havik et al., 2012). Using such computerized tasks, one can differentiate the following four methods: verbal duration estimation of a presented time span, duration production, duration reproduction of a previous interval or continuously presented intervals (tapping tasks), and duration discrimination between two intervals (Allan, 1979; Wittmann, 1999; Zakay, 1993). Alternatively, subjects are asked to estimate how much time has elapsed since the beginning of a non-temporal task or an explicit waiting time (Danckert & Allman, 2005; Wittmann et al., 2017; Jokic et al., 2018).

Temporal preparation, also called temporal orienting of attention, is closely related to response inhibition tasks that assess “behavioral impulsivity.” These tests assess how a subject processes temporal information and responds to an upcoming target (Correa et al., 2010; Coull and Nobre, 1998). In other words, a subject knows that a stimulus will be arriving after a given interval, and their use of that information to respond to the stimulus is evaluated. It is measured in a variety of ways, including a go-no-go task with added time intervals before stimuli to measure temporal preparation (Correa et al., 2010).

A further crucial aspect of time perception, which will be highlighted, is temporal orientation regarding the past, present, and future. An individual’s time orientation dynamically changes according to transient situational demands, but it can also be interpreted as a more stable

trait. Since impulsive behavior is defined as reacting to the immediate situation without thinking about future consequences, the relative dominance of the present at the expense of the future (or a shorter future time horizon) can be seen as a personality trait in impulsive individuals (Zimbardo et al., 1997; Keough et al., 1999; Wittmann & Paulus, 2016).

Results from these tasks and inventories, individually and in combination, and in different populations with substance use disorders can help elucidate the relationship between impulsivity and time perception in addictive disorders and identify relevant constructs.

2.3 Relationship between time, impulsivity in substance use disorders

<Insert Table 1>

2.3.1 Results in Alcohol Use disorder

2.3.1.1 Results from delay discounting tasks

In alcohol use disorder, steeper delayed discounting might reflect altered treatment of time flow, but it is difficult to disentangle whether this alteration is a basal trait of impulsivity or a complex deficit related to the severity of the disease.

Studies have suggested that impulsivity might be a trait variable that reflects primary neurobiological alterations. Field et al. (2007) found that among adolescent drinkers, heavier drinkers discounted hypothetical monetary and alcohol rewards more steeply on a delay discounting task, and were slower on an alcohol Stroop task. In a study that looked at delay discounting and self-reported impulsivity, Dom et al. (2006) found early-onset alcohol use to be associated with steeper discounting of delayed rewards, and suggested that impulsive decision making is not just an effect of substance use, but could also be a trait variable that

reflects a more stable personality trait. Stevens et al. (2017) examined intentions to drink, alcohol consumption, and impulsivity measures in high risk young adults. Intention-to-drink between subjects mediated the association between daily alcohol consumption and delay discounting results on the self-report monetary choice questionnaire, but not delay discounting results on the two-choice impulsivity behavioral paradigm (TCIP). Authors suggest that this discrepancy points to the heterogeneous nature of impulsivity and to the difference between self-report measures and behavioral tasks.

Jones et al. (2017) found that drinkers with a family history of alcoholism (FHD) discounted delayed rewards more steeply, but that alcohol naïve FHD adolescents showed fewer impulsive choices. Life-time drinks and binge-drinking were also associated with steeper delay discounting. The authors conclude that the temporal nature of the association between impulsivity and alcohol use is unclear, i.e. whether it can be considered a risk factor or a symptom, and that perhaps both are driven by another underlying phenotype or shared genetic component. To examine the neural underpinnings of impulsive decision making in alcoholism, Oberlin et al. (2015) measured *in vivo* dopamine (DA) receptor binding, and found higher delay discounting to be associated with lower dopamine D₂ receptor availability in the right ventral striatum. The authors conclude that there are two possibilities to explain these results in alcohol use disorder; either there is a reward system deficiency that causes low DA receptor availability and a predisposition for addictive disorders, or instead, it is possible that higher endogenous DA corresponds to increased sensitivity to immediate reinforcement, and thus increased impulsive choices and addictive disorders. The authors also conclude that based on their results, impulsive choice is likely a risk factor that predisposes alcohol dependence. Once again, the authors do not mention the role of time, but as time perception has also been found to be generated by striatal dopaminergic

function (Coull et al., 2004, 2008a; Meck, 2006), the findings do implicate a relationship between an endogenous dopaminergic deficit, time perception, impulsivity, and addiction.

While other studies have suggested that impulsivity is associated with the severity of substance use, the relationship with time remains unclear. Using both a monetary and alcohol reward-discounting task in active alcoholics, abstinent alcoholics, and controls, Petry (2001a) found steeper discounting in alcoholic subjects vs. controls, and found this effect to be greater for alcohol than for money, in both groups. Taylor et al. (2016) also reported increased self-reported impulsivity in abstinent alcohol-dependent and poly-drug-dependent subjects, but no differences on behavioral measures. Furthermore, the investigators found that current users discounted rewards more steeply than the abstinent group, which could suggest either an effect of alcohol exposure, or severity and duration of dependence.

Takahashi et al. (2009) employed a monetary reward card task, in which subjects had to pick from two decks that offered immediate or delayed rewards of varying value, as well as a probability discounting task (the delay replaced with a probability of gaining the reward), and a loss-frame task (rewards replaced by hypothetical losses). They found that higher alcohol use correlated with stronger discounting of delayed monetary loss, but not gains, contrary to results from other studies that do find discounting of delayed gains. The authors suggest that this could be explained by the subjects being relatively light drinkers. The study also found that alcohol use was not associated with the probability of losses or gains, which could point to the importance of the delay variable and to the role of time in discounting tasks, given that alcohol use was only associated with delay discounting and not probability discounting. Takahashi et al. (2009) do propose two interpretations for the correlation

between alcohol use frequency and delay discounting of loss; either people that strongly discount delayed losses tend to drink more, or regular alcohol use causes a neuroadaptation that leads to delay discounting of loss. To introduce the variable of time, it is possible that either a time deficit leads to both discounting of delayed losses and increased alcohol use, or that alcohol use causes a change in time perception that leads to delay discounting.

Finally, Amlung & KacKillop (2011) found delay discounting rates to be highly consistent in alcohol users, but much less consistent at long delays. While the authors suggest that perhaps subjects are not accustomed to evaluating such long delays into the future, it is also possible that this inconsistency at long delays reflects a difficulty to conceptualize time or projection into the future, as has been found in other addictive disorders (Bickel et al., 2012).

Synthesis of these arguments points to the role of time in impulsivity in alcohol use disorder, but it remains difficult to disentangle these three dimensions. Moreover, the literature does propose the alternate interpretation that these alterations are not basal, but instead increase with the severity and duration of alcohol use. However, the lack of literature on the subject is critical and does not allow us to make a final conclusion.

2.3.1.2 Results from time estimation tasks

Alcohol use has been shown to accelerate the feeling of the passage of time, but this has to be confirmed.

There is a lack of recent literature specifically examining time perception in alcohol dependence. Alcohol consumption itself affects the sense of time. In controlled laboratory experiments, a relative overestimation of duration in the time range of milliseconds to seconds has been shown (Ogden et al., 2011). Longer durations in the time range of hours

are affected differently. Alcohol intake leads to the feeling of a faster passage of time in retrospect. This effect is probably related to impaired attentional capacities during alcohol intoxication (Ogden & Montgomery, 2012).

2.3.1.3 Summary

Overall, the literature on the relationship between impulsivity and time perception is very limited in alcohol use disorder and the role of time is not well described or studied. Nonetheless, compelling results on impulsivity in alcohol disorder, which could be further elaborated by assessing time perception, point to the importance of elucidating the role of time.

2.3.2 Results in Tobacco Use Disorder

<Insert Table 2>

2.3.2.1 Results from delay discounting tasks

In Tobacco use disorder, impulsivity is characterized by steeper delayed discounting and is correlated with predisposition to tobacco use, risk of relapse, and the ability to quit smoking.

Numerous investigations have shown increased impulsivity in tobacco use and addiction (Erblich & Michalowski, 2015; Yakir et al., 2007) and specifically steeper discounting of delayed rewards (Bickel et al., 1999; Baker et al., 2003; Heyman & Gibb, 2006; Hofmeyr et al., 2016; Sweitzer et al., 2008; Sheffer et al., 2014; López-Torrecillas et al., 2014a & 2014b; Reynolds & Fields, 2012; Miglin et al., 2017). Sweitzer et al. (2008) found that current smokers discount delayed rewards more than never smokers, occasional, and ex-smokers, but that delay discounting rates are not associated with the number of cigarettes per day.

Other authors also found increased impulsivity to be more related to tobacco dependence than to cigarette use in general (Yakir et al., 2007; Heyman & Gibb, 2006).

Current cigarette smokers discount delayed rewards at higher rates than both never-smokers and ex-smokers (Bickel et al., 1999). Given that ex-smokers and never-smokers were found to have similar delay discounting rates (Bickel et al., 1999), the authors suggested that either delay discounting can be considered a reversible effect of nicotine dependence, or a factor that determines the strength of dependence and ability to quit. Yet Reynolds & Fields (2012) reported that adolescents experimenting with cigarettes showed similar discounting rates to daily smokers, evidence that supports delay discounting as a risk factor for smoking cigarettes, and not as a consequence of cigarette use.

Baker et al. (2003) also examined delay discounting behavior in never-smokers and nicotine dependent current smokers, and found that current smokers discounted real and hypothetical monetary rewards at higher rates. Other authors have examined risk of relapse or continued use, and also found increased delay discounting and/or self-reported impulsivity to be a risk factor (Erblich & Michalowski, 2015; Sheffer et al., 2014; López-Torrecillas et al., 2014a & 2014b; Roewer et al., 2015).

Analysis of the literature also shows that delay discounting is stronger in tobacco users than in volunteers and might predict the risk of relapse. However, the relationship with time is not explored in delay discounting tasks independently of reward.

2.3.2.2 Results from time estimation tasks

Smoking leads to overestimating time.

Few studies have looked at time perception in tobacco use, though some authors have used parameters that capture the dimension of time. Hofmeyr et al. (2016) studied specific delay

discounting patterns by modeling discounting rates on a monetary choice questionnaire. They did not find evidence for more time-inconsistent discounting (defined as hyperbolic discounting vs. time-consistent discounting, defined as exponential discounting) among current smokers as compared to non-smokers. The authors suggest that among smokers, there were both those that discounted time-consistently, and those that discounted time-inconsistently. Yakir et al. (2007) showed that smokers have less stable reaction times when responding to targets on the Continuous Performance Task, a test of sustained attention, indicating unstable response patterns in time. While the study did not include time-estimation or delay-discounting tasks, this result does provide evidence of altered responding in time, in nicotine-addicted subjects with elevated impulsivity.

Another study (Sayette et al., 2005) examined the effects of craving, or the urge to smoke, on time perception. Smokers that abstained from smoking for 12 hours and had cigarette cravings, i.e. felt a strong urge to smoke, experienced a 45 second time interval as passing more slowly (Sayette et al., 2005).

Similarly, Miglin et al. (2017) found that smokers overestimated time during abstinence, compared to during usual-smoking. Smokers undergoing treatment were administered a delay discounting task, a time discrimination task in which subjects indicated the longer of two intervals, and a time reproduction task that asked subjects to retain the duration of a stimulus, and then reproduce it. While smokers overestimated time during abstinence, abstinence did not affect delay discounting rates, which were elevated overall in smokers. Moreover, changes in time reproduction and time discrimination during withdrawal did not predict relapse, while delay discounting results did. The authors conclude that decision making and time perception might then be unrelated processes, though the differences in temporal durations across the tasks most likely contribute to lack of an association found.

While the time reproduction and discrimination tasks asked for assessments of seconds, delay discounting tasks use delays measured in days.

Very few studies showed an overestimation for delays measured in seconds and a correlation between time overestimation and impulsivity in tobacco users.

2.3.2.3 Summary

Overall, the literature examining impulsivity in tobacco use disorder emphasizes the relationship between increased delay discounting rates and current cigarette use, higher dependence, relapse risk, and treatment outcomes. Furthermore, many studies interpret their findings as implicating elevated delay discounting as a predisposing factor and not a symptom of nicotine exposure, and genetic data corroborates this view (VanderBroek et al., 2016; MacKillop et al., 2015). In terms of time perception and impulsivity in tobacco use disorder, very few studies have specifically examined this relationship.

2.3.3 Results in Opioid Use Disorder

<Insert Table 3>

2.3.3.1 Results from delay discounting tasks

While fewer studies have examined impulsivity and delay discounting in subjects with opioid use disorder than other substance use disorders, studies showed increased measures of impulsivity and steeper delay discounting associated with opiate use (Karakula et al., 2016; Landes et al., 2012; Giordano et al., 2002; Madden et al., 1997).

Madden et al. (1997) and Kirby et al. (1999) both showed that heroin users discount monetary rewards more steeply than healthy controls. In heroin-dependent subjects undergoing buprenorphine treatment, Madden et al. (1997) found increased delay

discounting of both hypothetical heroin and monetary rewards, and that heroin cue rewards were discounted the most steeply. Kirby et al. (1999) showed that heroin dependent subjects had discount rates twice those of controls on a real monetary choice task, which correlated to self-reported impulsivity.

Karakula et al. (2016) corroborated these results; they found evidence that treatment seeking heroin-dependent patients showed increased delay discounting rates, compared with opioid users who only used prescription opioids. The authors conclude that heroin use is associated with greater clinical deficits among opioid use disorders, though they cannot ascertain if the increase in delay discounting is a result of or predisposing factor of heroin use. Moreover, increased self-reported impulsivity has been shown to be correlated with heroin use duration and reduced gray matter volume in the prefrontal cortex (PFC) (Qiu et al., 2013).

Landes et al. (2012) showed that buprenorphine treatment plus a variety of behavioral therapies can lead to decreased delay discounting over time in opioid dependent patients. The authors interpret this result as evidence that delay discounting rates are not a state or trait, but rather are stable under stable conditions, and can change when conditions change, evolving as an individual evolves. No association was found, however, between abstinence outcomes and delay discounting rates.

Opioid deprivation has also shown to increase delay discounting rates in opioid dependent subjects (Giordano et al., 2002). Delay discounting rates of both monetary and heroin rewards were significantly higher when drug-dependent subjects were deprived from buprenorphine, compared to rates just after administration, indicating that drug deprivation increases delay discounting rates. Also, the delayed heroin cue rewards were discounted more steeply than monetary rewards both during buprenorphine deprivation and treatment,

supporting past results in opioid use disorder (Madden et al., 1997) and other substance use disorders (Petry et al., 2001a) indicating that a substance of abuse is more discounted with a delay and preferred immediately, compared to a monetary reward. Evidence that opioid users so quickly show increased impulsivity during deprivation could help explain risky drug-seeking behaviors among opioid dependent individuals, and has important clinical implications. The authors suggested that opioid-dependent patients have a myopic temporal horizon, leading them to rapidly discount the value of delayed rewards, and to be most influenced by immediate rewards.

In sum, a small number of studies in opioid users showed an effect of delay on time discounting in the case of situations that increase impulsivity like drug deprivation and craving. This effect merits further examination.

2.3.3.2 Results from Time Estimation tasks

Alterations in time perception have also been found in opiate addiction for estimation of delays around a few seconds and for their projection in the future.

Petry et al. (1998) tested heroin dependent subjects with a variety of tasks including the Stanford Time Perception Inventory (STPI), the Future Time Perspective Task, and the Iowa Gambling Task (IGT). They found that overall, heroin users showed decreased sensitivity to delayed consequences and shortened time horizons. Specifically, heroin dependent subjects were less likely to win money on the card task and prioritized immediate gains over delayed losses, were less likely to predict and organize events in the future, and scored lower on future orientation on the STPI scale. Petry et al. (1998) propose that heroin users might have a truncated time horizon that could in turn decrease sensitivity to delayed consequences, and alter decision making. These results might suggest a relationship with impulsivity as it

was shown by other studies that have revealed an overestimation of time intervals in impulsive subject groups (Capella et al. 1977; Berlin et al. 2004; Wittmann & Paulus, 2008; Moreira et al., 2016).

Aleksandrov et al. (2005) examined time perception in heroin users with a time estimation task, and found both supporting and contradicting evidence for time alterations in heroin dependent individuals. The results showed that patients with heroin addiction do not estimate time intervals differently from healthy controls, outside of the withdrawal period. While experiencing withdrawal symptoms during the first two days of treatment, patients under-reproduced time intervals, were able to accurately reproduce 12-sec interval after 5 to 6 days, and like the healthy controls, over-reproduced after days 10-11. The authors interpret the under-reproduction during withdrawal as resulting from symptoms of anxiety and irritability, which can increase blood dopamine, and alter the balance of inhibitory and excitatory processes to increase excitation. While changes in dopaminergic transmission and excitation are also associated with impulsivity (Brewer & Patenza, 2008), impulsivity and arousal have often been found to increase the accumulation of time pulses and lead to overestimations of time intervals (Capella et al., 1997; Berlin et al., 2004; Wittmann et al., 2007). It is possible that the intensity of the withdrawal state altered both signatures of impulsivity and time estimation, or caused an overall time distortion.

In opioid users, the literature showed an overestimation of time for delays of seconds and a distortion of time that prevents them from projecting into the future. Nevertheless, the relationship with impulsivity remains uncertain.

2.3.3.3 Summary

Overall, as with other substance use disorders, the literature does not show a clear relationship between opiate use, impulsivity measures including delay discounting, and time perception. Compelling results show alterations in measures of time estimation, perception, and processing, as well as increased delay discounting and impulsivity measures, but factors including addiction duration and withdrawal status complicate results. No study examined both time estimation and delay discounting in opiate use disorder, though alterations were found in both in separate investigations.

2.3.4 Results in stimulant use disorder (cocaine and methamphetamine)

<Insert Table 4>

2.3.4.1 Results from delay discounting tasks

Steeper temporal delay discounting in stimulant addiction is associated with impulsive behaviours and might be associated with neurobiological alterations.

In cocaine addiction, Bickel et al. (2011) found that subjects discounted delayed rewards more steeply, especially for cocaine cue rewards compared to monetary rewards. When subjects had to evaluate the cocaine cue reward after a monetary award, they discounted the most steeply vs. evaluating the monetary reward first. Given that typical decision-making models do not explain these results, the authors suggest that cocaine-dependent subjects may evaluate choices differently and possess both an impulsive decision-making system that values drugs, and an executive decision system that does not value drugs as highly. Other studies have confirmed these results in stimulant users, cocaine and methamphetamine users (Crunelle et al., 2013; Johnson, 2012; Hoffman et al., 2008).

Stevens et al. (2015a) investigated delay discounting and treatment outcomes in heterogeneous substance-dependent individuals, 70% of whom were cocaine users. High

delay discounting rates before treatment predicted shorter treatment retention and higher odds of premature treatment drop-out, which was partially mediated by treatment readiness. The same team again looked at impulsivity and treatment outcomes in substance dependent subjects (Stevens et al., 2015b), among whom 76% were cocaine users. They found that delay discounting results and impulsive decision-making on the IGT predicted short-term relapse, an association that was mediated by treatment retention. Relapsed and abstinent subjects did not differ on an impulsive action test, and the authors propose that motor inhibition could be involved in an earlier stage of addiction.

Drug use itself has also been found to be associated with impulsivity measures. Hulka et al. (2015) tested cocaine-dependent subjects that increased, decreased, or did not change their drug consumption over one year. Delay discounting results and performance on Rapid Visual Processing, a cognitive impulsivity task, did not change across groups, whereas BIS-11 and IGT results were found to co-vary with cocaine use, however in different directions. Subjects with increased drug use showed increased BIS-11 scores, and subjects with decreased consumption showed lower scores. Subjects that increased drug use improved their IGT scores, while subjects that decreased their drug use showed lower scores. Overall, the authors conclude that while self-reported and decision-making impulsivity could depend on drug use and be state-dependent, increased delay discounting may be a potential endophenotype of cocaine addiction.

Further studies have found evidence for a neurobiological mechanism underlying steeper delay discounting in stimulant addiction. Ballard et al. (2015) revealed that in subjects with methamphetamine dependence, lower striatal D₂ and D₃ receptor availability corresponds with steeper temporal delay discounting, indicating that deficient dopamine neurotransmission might contribute to delay discounting in drug addiction. Striatal D₂/D₃

receptor availability, which has been found to modulate PFC activity involving goal directed choices and decision making, is implicated in delaying gratification, and especially in stimulant users. BIS-11 scores also correlated negatively with receptor availability, but were not associated with delay discounting results, which could indicate that trait impulsivity and temporal discounting are at least partially separate constructs. The authors propose that deficient striatal D₂/D₃ receptor availability could explain why individuals keep using drugs despite negative consequences, and that treating this deficiency could help in stimulant addiction.

2.3.4.2 Results from time estimation tasks

Other lines of investigation have shown time overestimation in stimulant addiction.

Wittmann et al. (2007) found that cocaine and methamphetamine dependent subjects in a drug-treatment program overestimated the duration of a long 53-second time interval. They also showed accelerated finger tapping when an auditory pacing stimulus was removed in a paced motor timing task, and required larger time differences in order to discriminate between durations around one second. Increased impulsivity was found to mediate the overestimation of the 53-second interval.

Wittmann et al. conclude that altered time processing in stimulant-dependent subjects could explain their difficulty in delaying gratification, and that increased impulsivity accounts for the overestimation of the 53-second interval. Temporal processing deficits were expected in stimulant-dependent subjects, given that cocaine and methamphetamine users show altered prefrontal and striatal dopaminergic function, and striatal and PFC dopaminergic circuits are involved in impulse control, attention, working memory, as well as time perception. As they used a cross-sectional design, the authors could not conclude whether stimulant

dependence leads to altered temporal processing or vice versa, but do propose that temporal processing changes in stimulant use disorder result from fronto-striatal dysfunction. Altered time perception could result from stimulant-dependence-related brain changes, or altered time perception could precede and predispose stimulant addiction.

2.3.4.3 Summary

In stimulant dependence, increased measures of impulsivity and steeper delay discounting have been found and linked to dopaminergic function and alterations of the frontal cortex. Wittmann et al. (2007) found clear evidence of altered time perception, indicative of a relationship between time processing, impulsivity, and addiction in fronto-striatal dopaminergic circuits.

2.3.5 Results in Cannabis Use Disorder

<Insert Table 5>

2.3.5.1 Results from delay discounting tasks

Chronic cannabis use has been associated with multiple cognitive changes (Lalanne et al., 2017) including increased impulsivity and delay discounting rates but the relation to time is not explored.

Heinz et al. (2013) investigated delay discounting rates in cannabis users and found that higher rates correlated with younger age of first cannabis use, early start of regular use, seeking help for quit attempts, and higher compulsive craving. Cannabis cessation outcomes were unrelated to delay discounting rates, perhaps indicating that delay discounting is only sensitive to the developmental trajectory of cannabis use disorder, but not cessation results. Another study examining cannabis use in adolescents found that exposure to cannabis is associated with increased impulsive and risky decision making (Solowij et al., 2012). Poor

reflection impulsivity was also found to be associated with younger age of first use and greater exposure to cannabis, and the authors propose an altered serotonergic system as the underlying cause.

Delay discounting rates have also been shown to predict substance use treatment outcomes in adolescents (Stanger et al., 2012). Overall, adolescents receiving treatment for cannabis use were found to discount smaller magnitude rewards more at treatment onset, on a task that required evaluating a \$100 or \$1,000 reward. Delay discounting of \$1,000 during treatment predicted abstinence, across treatment types. Lee et al. (2015) compared delay discounting in adolescents and adults in treatment for cannabis use disorders. They found that adolescents discounted delays more steeply overall at the start of treatment, but adults showed greater discounting of \$100 than \$1000. Over the course of treatment, adults decreased discounting of cannabis rewards. Adolescents were less sensitive to reward magnitude changes, discounted money at higher rates, and showed less improvement (decreased discounting rates) overall. This investigation showed age differences in delay discounting among cannabis users, as well as differential changes in discounting over the course of treatment. But the relationship to time variation in these tasks was not examined in cannabis users.

Johnson et al. (2010) found that dependent cannabis users discounted cannabis rewards more steeply than money on a hypothetical delay discounting task (and discounted both rewards more steeply than controls). In those cannabis dependent individuals, a sense of powerlessness over the future (measured with the Present-Fatalistic subscale of the STPI) correlated with money and cannabis reward delay discounting. While powerlessness over the future is a subjective measure of how an individual feels about time, the correlation with delay discounting results could suggest an actual relationship.

Cannabis use is associated with impulsivity and stronger delay discounting that vary according to time and treatment. The relationship to time remains to be explored.

2.3.5.2 Results from time estimation tasks

Acute THC intake might have a different impact on time estimation and reproduction, according to the delays used in the tasks.

High doses of THC, the active chemical in cannabis, have been found to alter temporal processing. Sewell et al. (2013) administered increasing doses of THC in healthy individuals and measured time estimation and interval reproduction. All acute THC doses were found to induce overestimation of duration and interval underproduction, but chronic cannabis use had no effect on baseline time perception. The authors concluded that a psychoactive THC administration accelerates the internal clock speed, leading to time underproduction and time overestimation.

Acute effects of THC administration in healthy controls were found to include impulsive responding on the Stroop task, over-reproduction of short time intervals (2 and 4 second intervals), but no changes in reproduction of longer intervals (8, 16, and 23 second intervals) (McDonald et al., 2003). No changes were found on the Go/no-go or probability discounting tasks. McDonald et al. (2003) interpret the dissociations between these measures of impulsivity as evidence that impulsivity is an assemblage of distinct components rather than one construct. While more recent results found cannabis use to cause overestimation and under-production of time intervals in the multiple seconds range (Sewell et al., 2013), indicative of an acceleration of the internal clock, this study found that THC led subjects to over-produce the 2 sec and 4 sec time intervals.

Overall, these differences are most likely due to the time interval being evaluated.

2.3.5.3 Summary

In cannabis use disorders, both increased impulsivity and altered time perception have been found, specifically overestimation of time durations, but the relationship remains under-explored. Systematic studies are needed that include established time estimation and delay discounting tasks pertaining to similar time ranges.

2.3.6. Relationship between time, impulsivity in Gambling Disorder

<Insert Table 6>

2.3.6.1 Results from delay discounting tasks

Many studies over the past decades have pointed to a relationship between impulsivity, especially as measured with delay discounting tasks, and pathological gambling.

Petry and Casarella (1999) and Petry (2001b, c) found that not only do pathological gamblers discount delays more steeply when choosing hypothetical monetary rewards than controls do, but that pathological gamblers with substance use disorders discount delayed rewards at even higher rates.

Petry (2001b) first used a variety of self-report questionnaires to evaluate impulsivity indices in pathological gamblers with and without substance use disorders. They found that substance use and gambling together had an additive effect on impulse control, novelty seeking, and time orientation, as measured with the Stanford Time Perception Inventory (STPI), and combined these measures to assess impulsiveness. In a further study on delay discounting, Petry (2001c) used a hypothetical monetary reward task in gamblers with and without other substance use disorders, and found that gamblers had elevated delay discounting rates, and that gamblers with substance use disorders had even steeper rates.

The authors proposed that temporal discounting is relevant for understanding the relationship between impulsivity and the development of substance use disorders, and that increased discounting could predict later disorders. However, the study did not assess the directionality or temporal nature of the relationship between these factors of impulsivity and addiction. Alessi and Petry (2003) found gambling severity assessed with the South Oaks Gambling Scale (SOGS) to be a predictor of variance in delay discounting. The authors suggest that rapid discounting is a feature of addictive disorders.

Another study found that delay discounting results do not remain constant in pathological gamblers when the context is altered (Dixon et al., 2006). Subjects discounted delays more steeply in a gambling context than in a non-gambling context, suggesting that delay discounting can be induced or attenuated, and is not a stable attribute, as other studies have suggested (Bickel et al., 2001). One possibility is that gambling within the casino context represents a highly stimulating cue for pathological gamblers, which increases impulsivity and craving (Miedl et al., 2014; Dixon et al., 2006).

Other studies have found that pathological gambling is associated with stronger monetary delay discounting than alcohol or cannabis use disorders, underlining the problem with using a task to measure impulsivity that contains both monetary reward (the primary incentive for gamblers) and time delay (Stea et al. 2011; Johnson et al. 2010). If in delay discounting tasks, rewards related to a subject's addictive substance are discounted more steeply, or in other words are wanted more immediately, then increases in discounting can be considered a modifiable behavior and perhaps just a symptom of reward system pathology.

These results highlight that pathological gamblers show increased delay discounting, which is correlated with impulsivity on other measures. However, it is difficult to infer the role of time processing in these alterations.

2.3.6.2 Results from time estimation tasks

Multiple studies have examined and found associations between time perception and impulsivity in pathological gambling.

Hodgins & Engel (2002) examined time horizons in pathological gamblers with the Zimbardo Time Perspective Inventory (ZPTI), and the Future Time Perspective Inventory (FPTI). They found that pathological gamblers showed significantly shortened time horizons than social gamblers, and were relatively more focused on “current pleasures” and less oriented towards future events. Almost no differences were shown between the pathological gamblers and psychiatric patients. The authors suggest that shortened time horizons are perhaps not specific to addictions (like gambling disorder) versus other psychiatric disorders. When psychological distress was assessed as a common factor, the groups did differ more, but not significantly. The authors did not examine impulsivity with classic measures as a factor that could have been present in both psychiatric patients and the gamblers.

Based on findings in healthy controls that showed enhanced episodic future thinking (EFT) can decrease delay discounting (Bromberg et al., 2015; Benoit et al., 2011; Cheng et al., 2012; Peters & Büchel, 2010.), Wiehler et al. (2015) examined delay discounting, time perception, and episodic future thinking (EFT) in pathological gamblers. The authors measured delay discounting with a binary choice computer task, EFT with the Autobiographical Memory Interview (Levine et al., 2002), and time perception with a novel time interval rating task where subjects adjusted the size of circles. Results showed time perception to be best accounted for by a power law in both gamblers and controls, and the degree of non-linearity on the time perception task was associated with discounting rates in both groups, contrary to the hypothesis that impulsive choice might be in part due to

prospection deficits in gamblers. The groups were different in baseline EFT, only gambling status was associated with increased delay discounting, and depressive symptoms were related with attenuated discounting. Among gamblers, more vivid EFT tended to be associated with less delay discounting, suggesting an association between better future prospection and less impulsive discounting. It was also noted that while pathological gambling might not be associated with deficits in EFT and time perception, other substance use disorders could show such deficits. Overall, the authors concluded that elevated delay discounting in gamblers is not likely due to a general deficit in future prospection or evaluation of time delays.

Goudriaan et al. (2006) compared subjects with pathological gambling disorder, alcohol use disorder, Tourette syndrome (as an impulse-control disorder), and healthy controls on a neuropsychological battery assessing executive and cognitive functions. The investigators included sense of time as a measure of executive function, that requires intact prefrontal cortex and subcortico-cortex network functioning, and assessed it with a time interval estimation and reproduction task. Pathological gamblers and alcohol dependent users had worse performance on inhibition, cognitive flexibility, planning, and time estimation (over-estimation as compared to healthy controls). The results suggest a common neurocognitive etiology for gambling and alcohol use disorders, given the similar results, as well as a frontal lobe circuitry dysfunction in both disorders.

It is worth noting that while the authors did not examine impulsivity with common measures, besides time perception the other two deficits found in addicted groups, i.e. inhibition and planning, both fall under the term impulsivity, by classic definitions (Caswell et al., 2015). This again suggests a link between time perception and impulsivity deficits in addictive disorders. The same team did report on follow-up data from the pathological

gambling group (Goudriaan et al., 2007) and again assessed executive and cognitive function, this time also implementing the BIS-11, IGT, Card Playing Task for decision making, and the BAS Reward Sensitivity Scale. Results showed that impaired decision making on the Card Playing Task, increased disinhibition on the Stop-Signal Reaction Time Task, and disordered duration predicted relapse in pathological gamblers, while self-report measures did not.

Noseworthy and Finlay (2009) took a different approach and assessed the effects of auditory context on estimates of time during gambling by comparing ambient casino sound to ambient casino sound with music. They found that with no music, the more typical casino environment, subjects underestimated durations of play-time, whereas slow-paced music led to more accurate duration estimates of elapsed time and faster responses. The authors propose that music provides interval timing cues that are otherwise missing while subjects are gambling. Given the model of the internal clock, this result could suggest that music helps subjects accumulate time cues more accurately (Wearden, 2017; Zakay & Block, 1997). This result is significant, both for showing distorted time perception in pathological gamblers, and by offering a clue as to how this distortion might be attenuated.

While the relationship between increased impulsivity and altered time processing in gamblers is not well defined, some studies find results that can be interpreted as showing convergence between increased impulsivity and altered time perception (Hodgkins & Engel, 2002; Wiehler et al., 2015; Goudriaan et al., 2006; Noseworthy & Finlay, 2009): either subjects underestimated playtime (Noseworthy & Finlay, 2009) or they overestimated intervals (Goudriaan et al., 2006).

2.3.6.3 Summary

Ultimately, the literature on gambling disorder shows both evidence of elevated impulsivity, often demonstrated by a preference for immediate rewards over delayed but preferred rewards, and evidence of altered time perception. **While the literature tends to show a relationship between altered time perception and impulsivity in gamblers, the question remains to be further investigated.**

2.4 Summary of results in substance use disorders and gambling disorder

<Insert Table 7>

The literature examining impulsivity and time perception in substance use disorders provides evidence of increased impulsivity in alcohol use disorder (Petry, 2001a; Field et al., 2007; Dom et al., 2006; Stevens et al., 2017; Taylor et al., 2016; Takahashi et al., 2009; Jones et al., 2017; Oberlin et al., 2015), tobacco use disorder (Erblich & Michalowski, 2015; Yakir et al., 2007; Bickel et al., 1999; Baker et al., 2003; Heyman & Gibb, 2006; Hofmeyr et al., 2016; Sweitzer et al., 2008; Sheffer et al., 2014; López-Torrecillas et al., 2014a & 2014b; Reynolds & Fields, 2012; Miglin et al., 2017; Roewer et al., 2015), opiate use disorder (Karakula et al., 2016; Landes et al., 2012; Giordano et al., 2002; Madden et al., 1997 Kirby et al., 1999; Qiu et al., 2013), stimulant use disorder (Bickel et al., 2011; Crunelle et al., 2013; Johnson, 2012; Hoffman et al., 2008; Stevens et al., 2014; Stevens et al., 2015; Hulka et al., 2015; Ballard et al., 2015) cannabis use disorder (Heinz et al., 2013; Solowij et al., 2012; Stanger et al., 2012; Lee et al., 2015; Johnson et al., 2010), and gambling disorder (Petry and Casarella, 1999; Petry, 2001b & 2001c; Alessi & Petry, 2003; Dixon et al., 2006; Bickel et al., 2001; Stea et al. 2011; Johnson et al. 2010).

Results concerning time perception in addictive disorders are rare, and studies that examined both time perception and impulsivity even rarer. In alcohol use disorder, literature on time perception is very limited and no article examined impulsivity and the sense of time. Results in tobacco use disorder have shown overestimation of time during abstinence (Miglin et al., 2017), less stable response time patterns on an attention task (Yakir et al., 2007), and time passing more slowly during withdrawal (Sayette et al., 2005). The relationship between time perception and impulsivity in tobacco use disorder has not yet been examined. Evidence has been found in opioid use disorder that suggests a shortened time horizon in heroin users (Petry et al., 1998), which could decrease sensitivity to delayed consequences, and alter decision making. Heroin users were also found to under-reproduce time intervals during withdrawal (Aleksandrov et al., 2005). One study specifically addressed time and impulsivity in stimulant use disorder; dependent subjects showed altered time perception (overestimated time intervals, an accelerated tapping rhythm, and difficulties discriminating between intervals), which could explain their difficulty in delaying gratification and increased impulsivity (Wittmann et al., 2007). In cannabis use disorder, acute THC was found to induce alterations in time processing (overestimation of durations and underproduction of intervals) (McDonald et al., 2003), but chronic use did not change baseline time perception. More literature does exist on time perception in gambling disorder, perhaps because time is more clearly implicated in compulsive behavior. Pathological gamblers were found to have shorter time horizons and to be less oriented towards future events than social gamblers (Hodgins & Engel, 2000), and both gamblers and alcohol-users over-estimated time intervals (Goudriaan et al., 2006). Another study, however, found that elevated delay discounting in gamblers is not likely due to a general deficit in future prospection or evaluation of time delays (Wiehler et al., (2015). One recent

study might be added in this context as an example for future studies with gamblers; users at-risk for social media addiction showed time distortions when comparing estimated vs. actual Facebook browsing times (Turel et al., 2018).

The current review did not report results in poly-substance use disorders in order to analyze the factors of impulsivity and time perception in each individual substance addiction, but evidence has shown increased impulsivity and specifically delay-discounting among poly-substance users (Moody et al., 2015; Moody et al., 2016)

Ultimately, while only few studies examine both time perception and impulsivity in substance use disorders and gambling disorder, the literature shows compelling evidence that the relationship is worth examining in further studies.

4. General Discussion

Overall, the literature shows that individuals with addictive disorders do discount monetary rewards more steeply than healthy controls (Bickel et al. 2012; Koffarnus et al, 2013), across addictions and across contexts. Moreover, there seems to be a link between altered time perception and impulsivity in psychostimulant (cocaine and methamphetamine) addiction (Wittmann et al., 2007), in tobacco and opioid addiction, but it is less clear in alcohol addiction and in gambling disorders, because of the lack of literature, and in cannabis addiction because of confounding factors.

The link between altered time perception and impulsivity in addictive disorders makes sense regarding the neurobiological mechanisms. Indeed, time expectation and perceived reward

value share anatomical pathways and neurobiological mechanisms. The neural substrates of time expectation are, among others, the striatal-thalamo-cortical loop including the prefrontal cortex (Coull et al., 2004, 2008a; Meck, 2006). The striatum is part of the mesolimbic dopamine (DA) system and is in particular involved in several reward frameworks; the prefrontal cortex is involved in the ability/disability to stop addictive behaviors which persist (Niv et al., 2007). An fMRI study conducted in healthy volunteers showed that the NAc and the anterior insula are engaged in the temporal precision of responses to rewarding cues (Tomasi et al., 2014). That study showed a direct link between successful temporal predictions of rewarding cues and the activation of NAc, as well as the involvement of the tegmental ventral area in error processing of temporal prediction. In accordance with a different conceptualization and empirical body of evidence pertaining to subjective time, impulsivity moreover can be understood as a strongly felt urge for immediate gratification, which is generated through the interoceptive system (Turel & Bechara, 2016). Both the cortico-striatal system and the anterior insula are involved in the processing of rewards with different delays (Tanaka et al., 2004; Wittmann et al., 2010). These two systems are part of the so-called 'core control network' (Cole & Schneider, 2007; Craig, 2009). Activations in the anterior insula Inferior, medial frontal cortex, and inferior frontal cortex were significantly correlated with reproduced duration as well as with impulsivity (as measured with the BIS) and future orientation (as measured with the ZTPI). The greater the activation in the core control network, the shorter the reproduced intervals, the more impulsive the individual, and the less pronounced their future perspective (Wittmann et al., 2011).

Moreover, neurobiological pathways that are involved both in reward- and time-perception are involved in impulsive behavior. Although there are at least three different

types of impulsivity, namely motor, waiting and reflection impulsivity, their neural networks all involve cortico-striatal loops and the prefrontal cortex (Dalley et al., 2011). Also, time perception, impulsivity and reward processing share neurobiological mechanisms and we highlighted robust evidence for altered impulsivity, delay discounting, and time perception in addictive disorders. However, the nature of the relationship between addiction, impulsivity, and time perception remains unclear, as does the directionality of the link between exposure to addictive substances, measured impulsivity, and time perception. Some authors have posited the existence of a third variable that ties impulsivity and addictive disorders together, and we seek to propose that this underlying factor might be time processing. Given overlapping neurobiological substrates of time perception, impulsivity, and addictive disorders, as well as patterns in behavioral data, this does merit further investigations to test the relationship between abnormal time processing and impulsivity in addictive disorders. Two hypotheses are proposed and debated in the literature.

Wittmann et al (2007) found that subjects dependent on psychostimulants show an overestimation of time that is correlated with their level of impulsivity. These results suggest that, in impulsive people, an acceleration of the internal clock (or more attention paid to time) provokes an overestimation of elapsed time and premature reactions. According to this hypothesis, the acceleration of the internal clock (or increased attention paid to time) would lead patients to judge that the delay before obtaining a reward is too long, and in turn could provoke impulsive responses (see fig. 3). Another possibility was proposed by McGuire and Kable (2013) who assume that patients' impulsivity could be affected by a disorder of time flow. In this way, subjects would be lost in time and would have difficulties predicting events in time. This could lead them to develop maladaptive strategies to adapt to their

environment that lead to impulsive behaviors. As such, impulsivity might be driven by an abnormal time expectation rather than clock acceleration (see fig. 3).

These two hypotheses result from observing correlations between time overestimation and impulsivity in patients suffering from addictive disorders. It is difficult to infer directionality and causality from correlations stemming from cross-sectional studies and to precisely determine the cause of abnormal time processing in people who suffer from impulsivity and addictive disorders. Whatever the directionality of the relationship between time perception and impulsivity in addictive disorders, it is well known that addictive behaviors both lead to and are anteceded by cognitive impairments separate from time distortions, including working memory, mood, and attention deficits (Lalanne et al., 2016). These deficits could in turn have an impact on time perception at numerous stages of time estimation with respect to the internal clock model (see fig. 3). It is therefore possible for a time disorder to generate impulsive behaviours. Disordered time perception could be both a predisposing risk factor of addiction, and contribute to the symptoms of substance use when exacerbated by an addictive substance.

Also, defining the relationship between time perception and impulsivity in addictive disorders might help to explain how the tendency to choose an immediate gratification over a delayed and preferred reward could result from time disturbances. New studies must be conducted to address this problem and to differentiate between the two hypotheses.

<Insert Colored Figure 3>

Understanding how disordered time perception affects impulsivity and vice versa in addictive disorders may have important therapeutic implications. Interventions aimed at improving patients' ability to process time could attenuate impulsive behaviors, and even reduce the need for immediate gratification. Changing the auditory environment to provide

temporal cues (Noseworthy and Finlay, 2009) could, for example, make it easier for patients' to wait for a reward. Individuals struggling with addictive disorders might also benefit from methods for perceiving time differently. For an individual addicted to a drug, the benefit or reward of resisting the temptation to use the drug, i.e. to delay gratification, might lie subjectively too far in the future. Programs should be developed to modulate subjective awareness of time. For example, when choices are linguistically framed in a way that one cognitively "jumps" in time towards a future option, one feels situationally closer and is more likely to choose a delayed reward or option (Polunin, 2015). Through manipulations such as directing attention away from time and towards a goal in inter-temporal decisions, (in this context, the goal is not to relapse) individuals show stronger preferences to wait (Ebert & Prelec, 2007). Some interventions might eventually target the timing system directly. This would affect the way patients with substance abuse process time and thereby structure behavior towards health-promoting actions.

It is also important to examine how other risk factors, such as attentional and mood disorders or other psychiatric comorbidities might influence time processing in impulsive individuals with addictive disorders.

Conclusion

Addiction is known to lead to cognitive deficits, which are related both to the toxicity of the substance and addictive processes. These alterations might have an impact on decisional processes, short term memory, and time perception, and could increase normal or elevated impulsivity levels to pathological impulsivity. In this way, addictive behaviors are a good model for understanding the pathophysiology of impulsivity and could help us to better understand the relationship between time perception and impulsivity in addictive behaviors

and disorders. New experimental protocols including longitudinal designs are needed to examine the pathophysiology of the complex construct known as impulsivity.

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Figure Captions

Figure 1. The Internal Clock : In this cognitive model of time perception, an internal clock measures perceived time flow with a **pacemaker** and an **accumulator** unit (Treisman, 1963). The **pacemaker** generates pulses during a given interval, which are read and counted by the **accumulator**. The number of counted pulses during that interval then represents its duration. In attentional gate models, pulses are only registered when attention is directed to time and a **switch** closes, thus opening the gate from **pacemaker to accumulator** and allowing pulses to be read and counted (Gibbon et al., 1984; Wearden, 2017; Zakay & Block, 1997). Once perceived time is accumulated, it affects **memory, decision making, and behavior**. The feeling of time is influenced by **mood states**, which determine **attention** allocation and **arousal**. Increased attention to time leads to increased **accumulation** of pulses, and increased arousal speeds up the **pacemaker** and also leads to increased **accumulation** of pulses in an interval (Droit-Volet & Meck, 2007; Wittmann & Paulus, 2008). Impulsivity has been shown to increase cognitive tempo, and lead to a slower passing of time (Lawrence & Stanford, 1999), so pathologies associated with elevated impulsivity, including addictive disorders, likely affect the internal clock (Berlin et al., 2004 ; Gonzales-Garrido et al., 2008 ; Wittmann et al., 2007). Addictive disorders are also known to have an impact **on mood states, attention, and arousal**, and symptoms include **short-term memory** deficits and impaired **decision making** (Lalanne et al., 2016b). Given the internal clock model, and results reviewed in this article that show elevated impulsivity altered time perception in addictive disorders, we propose that **addiction** might also affect the **accumulator**.

Figure 2. Delay Discounting : Tasks that measure delay discounting, the tendency for people to prioritize the immediacy of a reward over its value, often ask individuals to choose between an immediate reward and a delayed but more valuable reward. In this example, the subject would be asked to choose between 20 euros immediately or 60 after a given delay. Both reward and delay quantities would then be successively changed in order to measure the subject's subjective threshold for valuing the time delay vs. monetary gain. The graph shows that for individuals high in impulsivity (in red), this threshold is high: subjects choose the rewards at shorter delays, and discount rewards at longer delays, compared to healthy volunteers (in blue).

Figure 3. Two hypotheses: The current review proposes two hypothesis for the relationship between impulsivity and time, which are illustrated in this figure. According to the first (on the left), an acceleration of the internal clock leads to over-estimating passing time, and then an impulsive response results. In the second hypothesis (on the right), a time anticipation disorder leads to an inability to predict events in time, thus maladaptive strategies results and lead to impulsive response.

Figure 1

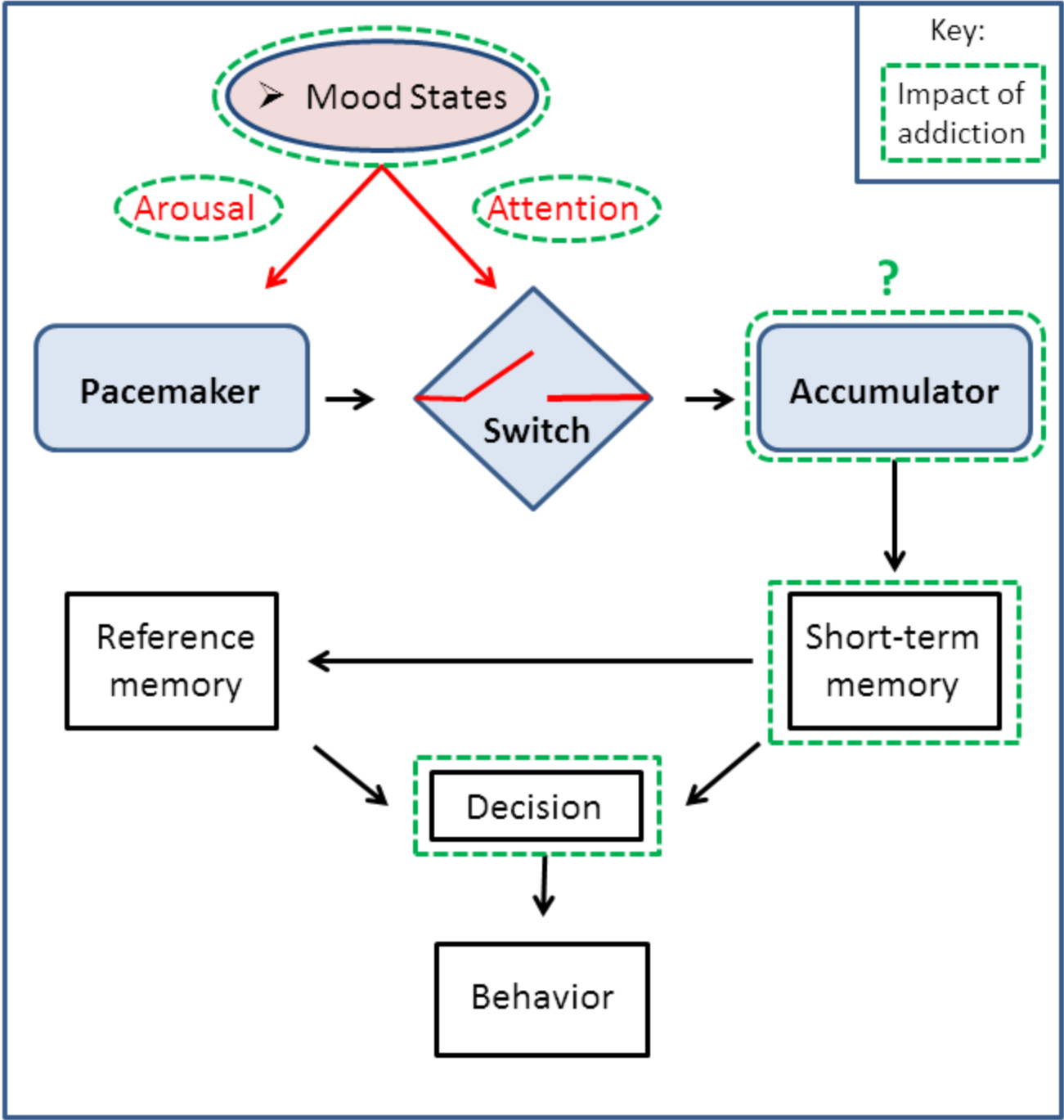


Figure 2

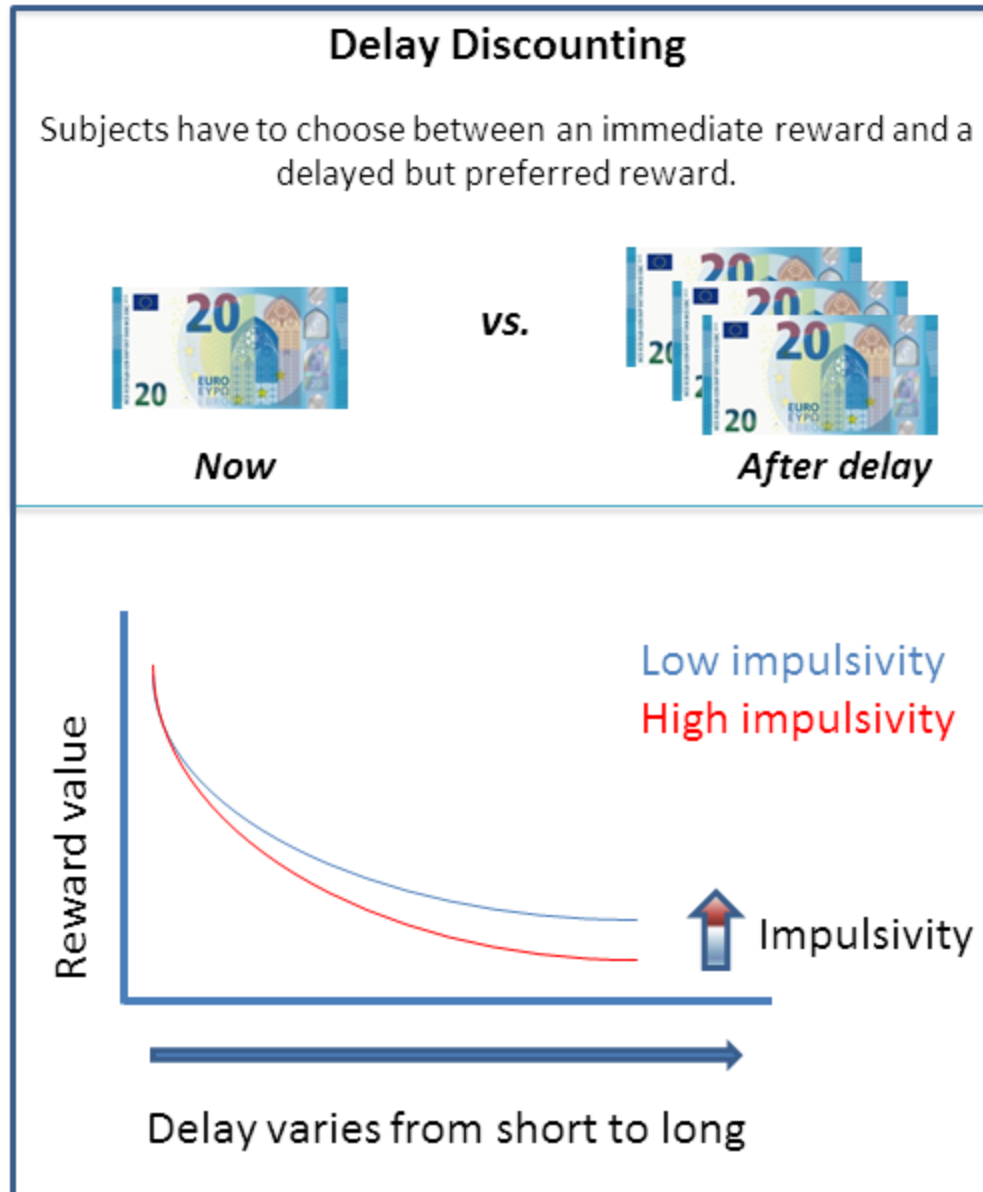
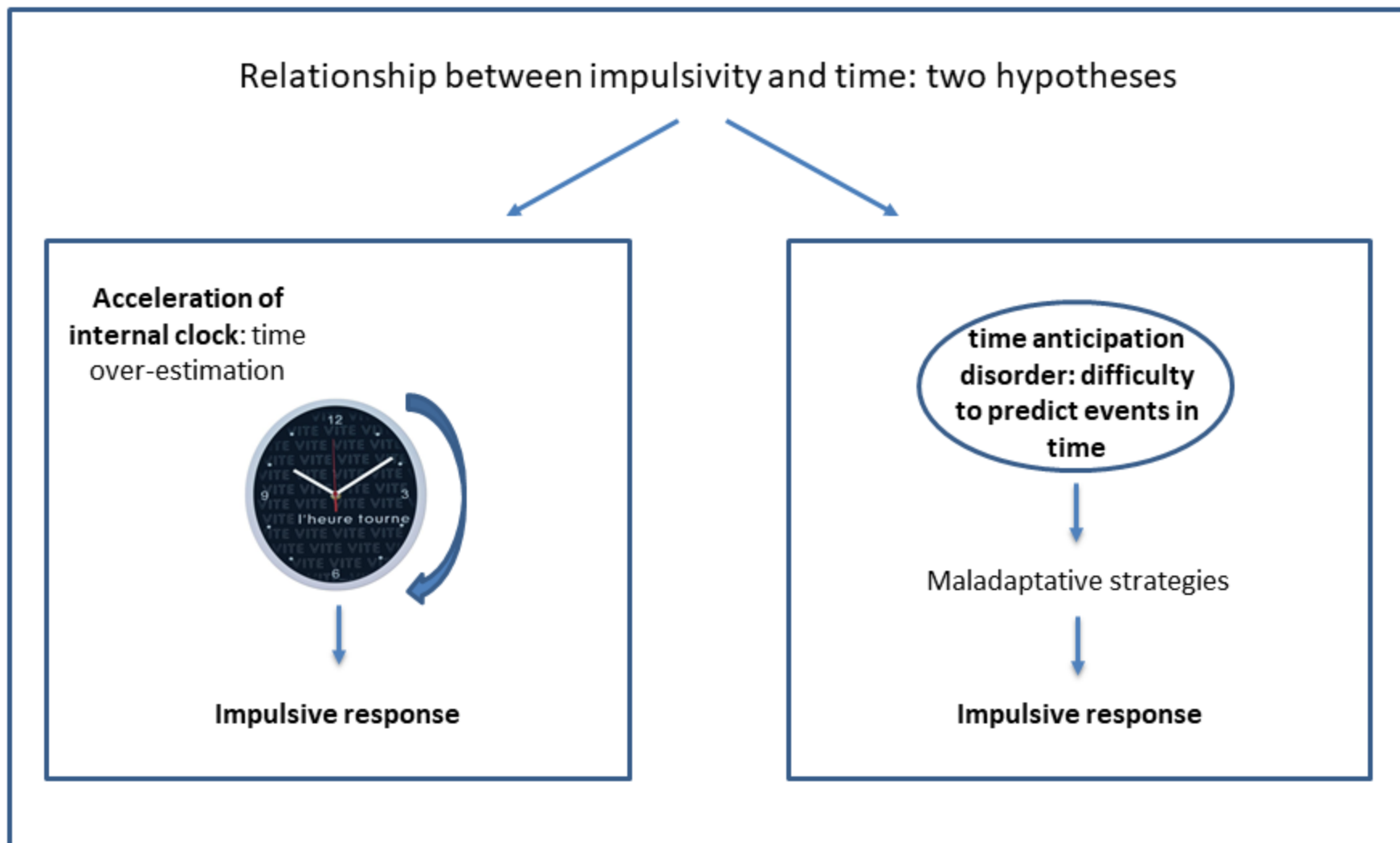


Figure 3



Article	Population Tested	Study Design	Tasks/Parameters	Main Results Concerning Impulsivity and/or Time Perception	Interpretation or Theory Proposed
Petry, 2001a	Active alcohol users (n = 12), abstinent former alcohol users (n = 12), and controls (n = 15)	Subjects assessed for alcohol use and completed different delay discounting tasks of money and alcohol. Between subject design.	Verbal delay discounting task (DDT) with hypothetical monetary and alcohol rewards.	Alcohol was discounted at delays more rapidly than money. The active alcohol users had the most rapid discounting rates, followed by abstinent former users, then controls.	Rapid discounting of delayed rewards could be a feature related to addictive disorders, and it is important to understand how delaying rewards in time changes their value.
Field et al., 2007	Adolescents (n = 90) identified as heavy or light alcohol drinkers.	Between-subjects design: subjects assessed and grouped by alcohol use, and tested for craving, delay discounting, and on a Stroop task.	Written DDT with hypothetical monetary and alcohol rewards; Stroop task with neutral and alcohol-related stimuli.	Heavy drinkers discounted delayed monetary and alcohol rewards more than light drinkers. Delay discounting results correlated to attentional bias on Stroop task, and to alcohol use and craving.	Heavy alcohol use in adolescents associated with short-term focus in decision making and biased attentional processing of alcohol-related cues.
Dom et al., 2006	Early-onset alcoholics (EOAs) (n = 42) late-onset alcoholics (LOAs) (n = 46), and healthy controls (n = 54)	Subjects given delay discounting task and cross-sectional survey to assess substance-abuse, impulsivity, and aggression. Between-subject and between-group design.	European Addiction Severity Index; Barrett Impulsiveness Scale (BIS); Zuckermann Sensation Seeking Scale (SSS); Buss-Durkee Hostility Inventory; DDT with hypothetical monetary rewards	EOAs scored higher on impulsivity measures (BIS and delay discounting task) and scored higher on the severity of substance-reacted problems.	Evidence that EOAs are more impulsive than LOAs, and that identifying alcoholism subtypes based on impulsivity dimensions could be relevant for treatment.
Stevens et al., 2017	High-risk young adults (n = 77)	Subjects self-reported daily intention to consume alcohol and alcohol consumption for 10 days. Assessed for impulsivity constructs. Within-subject and between-subject design.	PUPS-P Impulsive Behavior Scale; Monetary Choice Questionnaire (MCQ); Two Choice Impulsivity Paradigm (TCIP); Go-Stop Task; Immediate Memory Task (IMT); Self-report alcohol intentions and usage.	Subjects with high lack of planning and positive urgency results on the UPPS-P impulsivity scale had greater intentions to drink, predicting increased alcohol consumption. Intention-to-drink between subjects mediated the association between daily alcohol use and monetary choice questionnaire results.	Among individuals higher in impulsivity, drinking intentions are relevant and could help treatment providers address potential replacement behaviors to reduce alcohol consumption.
Taylor et al., 2016	Abstinent substance-dependent (AbD) subjects (alcohol, n = 27; poly drug, n = 59) and controls (n = 57)	All groups completed self-report measures of impulsivity and behavioral tasks, including one during fMRI. Between group design.	BIS; UPPS Scale, Behavior Inhibition/Activation System (BIS/BAS); Obsessive-Compulsive Inventory; Stop Signal; Intra-Extra Dimensional Set-Shift; Kirby DDT; Go/NoGo during fMRI	AbD groups scored higher on self-report measures; alcohol and polydrug groups did not differ. Polydrug group had highest delay discounting scores. Length of abstinence related to impulsivity measures (scores on subsets of BIS-11, UPPS-P, BIS/BAS, and Kirby DDT).	Self-report measures are more sensitive to impulsivity in long-term abstinent individuals than behavioral or neuronal measures. Important to develop behavioral measures for different aspects of impulsivity.

Takahashi et al., 2009	Adult subjects with varied alcohol use (n = 33)	Participants completed tasks of delay and probability discounting of gains and losses, and alcohol use was assessed. Between subject design.	Computerized delay discounting task and probability discounting task with hypothetical monetary rewards.	Frequency of alcohol use significantly correlated to strong discounting of delayed monetary losses. No correlation between alcohol use and probability discounting or delay discounting of gains.	Frequent alcohol use may be associated with increased degree of procrastination, and delay discounting of loss could be a predictor of frequent alcohol intake.
Jones et al., 2017	Alcohol-naïve adolescents (n = 116) with and without familial alcoholism (FHD). Grouped based on remaining non-drinkers (n = 83) or initiating binge drinking (n = 33)	Subjects completed 2-4 visits; during each, assessed for alcohol use, FHD, and delay discounting. Matched controls for binge-drinking subjects. Within-subject and between-subject design.	Computerized and self-paced DDT with hypothetical and real monetary rewards.	In non-drinkers, greater FHD associated with steeper decrease in discounting rates across adolescence. Total life-time drinks predicted higher impulsive choice in binge-drinking subjects.	FHD interacts with binge drinking during adolescence and is associated with altered trajectory of impulsive choice over time. Important to understand how and why alcohol use is associated with the development of impulsive choice
Oberlin et al., 2015	Non-treatment seeking alcoholics (NTC) (n = 10) and social drinkers (n = 13)	Subjects underwent PET scans at baseline, and completed DDT and self-report measures outside the scanner. Between-subject design.	Impulsiveness Questionnaire; SSS; RAC-PET scan; Computerized DDT with hypothetical monetary rewards.	Greater impulsive choice for \$20 correlated with lower D2/D3 binding potential. NTS subjects showed greater self-reported impulsivity and impulsive choice. Problematic alcohol use negatively correlated to impulsive choice of big rewards across all subjects.	Subjects who undervalue future rewards also show low striatal D2 receptor availability; this could indicate a potential biomarker. Alcoholics' discounting of larger future rewards could reflect a generalized undervaluation of the future.
Amlung & MacKillop, 2011	Young adults with varied alcohol use (n = 111)	Alcohol use assessed and two DDT administered; response consistency and reward magnitude effects examined. Within subject and between subject design.	MCQ; computerized DDT with hypothetical monetary rewards.	Consistent performance across both the DDT and MCQ, but DDT results affected by delay and reward magnitude (more inconsistent choices for long delays and low rewards). More alcohol use and alcohol misuse associated with steeper delay discounting on the MCQ.	Results suggest a consistent template for DD preferences in individuals, but that the template varies by delay length and reward magnitude.
Ogden et al., 2011	Adult drinkers (n = 58)	Blind between-subjects design. Subjects administered placebo, 0.4 g/kg alcohol, or 0.6 g/kg alcohol, then completed temporal tasks.	Temporal Task: verbal estimation and temporal generalization, retrospective timing task, passage of time judgement task.	High dose of alcohol resulted in overestimations of duration vs. low dose and placebo on the verbal estimation task, as well as to judging time passing more quickly than normal.	A high dose of alcohol may increase internal clock speed and lead to the sensation of time passing quickly, and to over-estimations of durations on prospective timing tasks.

Table 1: Summary of original scientific articles included in the review that examine impulsivity and/or time perception in alcohol use disorder. Only results regarding impulsivity and time perception or processing are reported in this table.

Article	Population Tested	Study Design	Tasks/Parameters	Main Results Concerning Impulsivity and/or Time Perception	Proposed Theory
Erblich & Michalowski, 2015	Current dependent smokers, ≥ 10 cigarettes per day (n = 151)	Subjects assessed for impulsivity and previous quit attempts, and rated cigarette cravings before and after exposure to smoking cues. Within-subject and between-subject design.	Impulsive Sensation Seeking Scale (ISS); Cigarette Craving Questionnaire	Higher cue-induced craving related to shorter duration of previous failed quit attempts, especially in smokers with higher impulsivity scores.	Trait impulsivity should be considered a factor in understanding and managing cue-induced craving.
Yakir et al., 2007	Young female adults: current smokers (n = 91), past smokers (n = 40), non-smokers (n = 151), and occasional smokers (n = 46)	Groups assessed with neurocognitive battery. Between-groups and within-subject design.	CogScan battery with 16 tests: Reaction time task; Stroop Task; Continuous Performance Task (CPT); Choice reaction time and digit running; finger tapping test; memory recognition tests; working memory tests, Matching Familiar Figures Test (MFFT); Tower of London (TOL)	Current smokers made more errors than never-smokers on the CPT, MFFT, and TOP, and past-smokers made more errors than NS on the MFFT and TOL. PS and CS did not differ on any test.	Impairments in sustained attention and control of impulsivity could be a predisposing factor in young women who begin smoking to continue.
Bickel et al., 1999	Current smokers (n = 23), never-smokers (n = 22), and ex-smokers (n = 22)	All subjects completed DDT. Between-group and within-group design.	Eysenck Personality Questionnaire; Written DDT with hypothetical monetary and cigarette rewards.	Current smokers discounted delayed monetary rewards the most. Never and ex-smokers did not differ. Cigarette rewards lost value at delays more rapidly for current smokers.	Cigarette dependence characterized by delay discounting of rewards, especially of the drug of dependence. Smoking could be associated with a reversible increase in discounting.
Baker et al., 2003	Current smokers, ≥ 20 cigarettes per day (n = 30) and never-before smokers (n = 30)	Between-group and within-subject design. Subjects assessed with DDT.	Verbal/written and computerized DDTs with hypothetical monetary rewards, cigarette, and health rewards.	Both current and never smokers showed a magnitude, sign, and commodity effect on the DDT. Current smokers had higher overall DD rates for monetary rewards, and a trend towards higher DD rates for health outcomes.	Delay discounting may be a mechanism behind impulsivity, not just an index, and it could be caused by drug dependence.
Heyman & Gibb, 2006	Young adults (n = 71); regular smokers (n = 19), chippers (n = 21), or nonsmokers (n = 31).	Between-group and within-subject design. Subjects assessed with self-report measures and with DDT.	BIS-11; Procrastination Assessment Scale; Verbal/written DDT with hypothetical and real monetary rewards.	Regular smokers did not discount delays for real monetary rewards as often vs. never-smokers and chippers.	Chippers may be less impulsive than regular smokers. Delay discounting rates seem to decrease as a negative power function of the monetary value of rewards.
			MCQ		

Hofmeyr et al., 2016	Current smokers, ≥ 15 cigarettes per day (n = 163), ex-smokers (n = 208), and never smokers (n = 834)	Between-group design. DDT task implemented.		Current smokers had steeper discounting vs. never-smokers across all models. Current smokers were not more prone to time-inconsistent discounting.	Steep discounting found among smokers; treatment approaches might be specific to type of discounting behavior.
Sweitzer et al., 2008	Heavy, moderate, light smokers, former-smokers, and non-smokers (n = 710)	Evaluating smoking behavior and DD	DD task (monetary reward task)	Higher DD in current smokers, DD related to dependence and morning smoking on Fagerström, but not to cigarettes per day	DD could be marker for dependence, maybe not related to nicotine exposure.
Sheffer et al., 2014	Dependent smokers, ≥ 10 cigarettes per day (n = 90)	CBT & nicotine replacement therapy. Cognitive measures at baseline, 4 wks, and 27 wks after quit date	DD task, BIS-11, RLOC, PSS. Outcomes sorted into groups: abstinent, relapsed, drop-out	Higher DD of \$100 associated with fewer days to relapse & FTND, but BIS & RLOC not associated to DD or days to relapse.	DD of \$100 perhaps a strong prognostic indicator for treatment response; limited temporal horizon might impede treatment
López-Torrecillas et al., 2014a	Tobacco smokers seeking treatment for nicotine addiction (n = 113)	Assessments, then CBT + varenicline. Grouped by outcome after 1 month. Between groups, unifactorial design	DDT; Temperament and Character Inventory (TCI). Split into outcome groups: abstinent, relapsed, drop-out	Harm avoidance (HA) and DD show differences between groups; both are lowest in dropout, highest in relapse.	Smokers that relapse or drop-out of treatment may not inhibit behavior appropriately; personality profile necessary with treatment
López-Torrecillas et al., 2014b	Tobacco smokers seeking treatment for nicotine addiction (n = 140)	Naturalistic prospective study: subjects tested prior to treatment, outcomes assessed at 3, 6, 12 months	MCQ, TCI, BIS-11, Go/No GO, Iowa Gambling Task. Split into outcome groups: dropout vs. relapse vs. Abstinent	Novelty seeking, reward dependence, trait impulsivity predicted low treatment retention. Persistence, trait impulsivity, IGT predicted relapse.	Temperament and impulsivity predict smoking cessation outcomes: tailored intervention for impulse control recommended
Reynolds & Fields, 2012	Adolescent (n = 141) non-smokers (n = 50), experimenters (n = 41) and smokers (n = 50).	Between-groups study.	Computerized DDT with hypothetical monetary rewards; BIS-11	Smokers (both heavy and experimenters) discounted more by delay and had higher self-reported impulsivity than non-smokers.	Adolescents who experiment with cigarettes seem to resemble regular smokers, in terms of the tendency towards impulsivity
Miglin et al., 2017	Dependent smokers (n = 45)	Subjects assessed during two sessions: the first after 24-hour abstinence, the second after smoking as usual. Within-subject and between-groups study.	7-day monitored abstinence; Time Discrimination Task; Time Reproduction Task;	Smokers overestimate time during abstinence, but abstinence did not affect discounting rate. Higher discounting rates during abstinence predicted greater number of days absent.	Individuals who prefer immediate rewards during abstinence may be less likely to relapse if offered small, frequent monetary incentives.

			computerized DDT task with hypothetical rewards		
Sayette et al., 2005	Adult smokers not interested in quitting (n = 80)	Experiment 1: smokers divided into high or low-urge conditions, then administered time perception measures. Experiment 2: high-urge smokers either anticipated how urges could climb over next 45 abstinent minutes, or reported real urges.	45-s prospective timing measure; 90-s prospective timing measure; retrospective timing measure; anticipated urge scale	Group anticipating urges reported urges climbing steadily, while group reporting real urges did not. High-urge group estimated longer intervals vs low-crave group estimated time as passing more quickly.	Smoking urge may affect time perception; smokers during craving could overestimate durations and intensity of own future. Importance of temporal cognition for smoking research.
Roewer et al., 2015	Heavy smokers (n = 37)	Subjects completed DDTs during two sessions: one after 24 hrs of nicotine deprivation, and one normally smoking. Within-subject and between-subject design.	Computerized DDT with real monetary rewards; Stop Signal Response.	Nicotine deprivation had no effect on DD rates, but responses were much slower after nicotine deprivation.	Supports findings that nicotine deprivation does not affect choice impulsivity when choosing between smaller, real monetary rewards.
<p>Table 2: Summary of original scientific articles included in the review that examine impulsivity and/or time perception in tobacco use disorder. Only results regarding impulsivity and time perception or processing are reported in this table.</p>					

Article	Population Tested	Study Design	Tasks/Parameters	Main Results Concerning Impulsivity and/or Time Perception	Interpretation or Theory Proposed
Karakula et al., 2016	Opioid-dependent heroin or prescription drug users, undergoing buprenorphine stabilization (n = 139)	Subjects grouped as heroin users, prescription opioid users, or combined users. Assessed for dependence and DD. Between-group design, cross-sectional.	Brief Addiction Monitor; MCQ	Heroin use associated with higher delay discounting than prescription opioid use.	Further evidence of greater clinical severity associated with heroin use in opioid use disorder. Elevated DD could be possible risk factor for initiating heroin use.
Landes et al., 2012	Opioid-dependent individuals completing a 12-week buprenorphine and therapy treatment (n = 159)	Subjects completed DDTs at baseline and treatment-end after 12 weeks. Within-subject and between-subject design.	Computerized DDT with hypothetical monetary rewards; Abstinence outcomes evaluated	Overall delay discounting at 12 weeks decreased to less than half of baseline levels; most subjects individually decreased discounting from baseline. There was no relationship with abstinence outcomes.	Evidence suggesting that treatment for substance dependence promotes decreases in delay discounting, and that delay discounting might be a mutable quality.
Giordano et al., 2002	Opioid-dependent individuals maintained on buprenorphine (13)	Subjects completed DDT during 8 sessions under different conditions of opioid deprivation or satiation. Within-subject and within group (treatment condition) design.	DDT with 3 hypothetical heroin and money rewards	Delay discounting rates higher during opioid deprivation, higher for heroin than money rewards, and inversely related to reward magnitude.	Important to understand the conditions that affect delay discounting in drug-dependent individuals, to better understand their choices (like impulsive choices during withdrawal) and improve treatment outcomes.
Madden et al., 1997	Opioid-dependent heroin users enrolled in treatment (n = 18) and matched non-drug using controls (n = 36)	Both groups performed DDT. Between-subject design.	Eysenck Personality Questionnaire (with Impulsivity Subscale); Addiction Severity Index; Written DDT with hypothetical monetary and heroin rewards	Opioid-dependent subjects discounted delayed monetary rewards more steeply than controls, and discounted delayed heroin more than money.	Important to investigate if delay discounting precedes or follows substance abuse, given individual and group differences observed.
Kirby et al., 1999	Heroin-dependent individuals (n = 56) and matched controls (n = 60)	Both groups assessed with DDT and self-report measures. Between-subject design.	Written DDT based on MCQ with hypothetical and real monetary rewards; I-5 Questionnaire	Heroin users' delay discounting rates were twice as high as controls, and	Result provides support for external validity of DD rate as a measure of impulsiveness.

			(Impulsivity, Venturesomeness, Empathy subscales); BIS-10	positively correlated with self-reported impulsivity.	Understanding how DD affects decisions to use or not use drugs could be relevant for treatment.
Qiu et al., 2013	Heroin-dependent individuals on methadone maintenance treatment (n = 24) and matched controls (n = 24)	Both groups underwent structural MRI and very matter volume analysis, as well as a self-report measure of impulsivity. Between-subject design.	High-resolution structural magnetic MRI; Gray matter volume analysis with voxel-based morphometry; BIS-11	Cortical gray matter volume in bilateral medial add dorsal lateral PFC, and right fusiform cortex reduced in heroin users. Gray matter volume in PFC negatively correlated with heroin use duration and self-reported impulsivity.	Evidence for structural changes in heroin dependence, possibly related to duration of heroin use and impulsive behavior.
Petry et al., 1998	Heroin-dependent individuals on buprenorphine treatment (n = 34) and controls (n = 59)	Both groups completed self-report and behavioral tasks. Between-subject design	Stanford Time Perception Inventory (STPI); Future Time Perspective (FTP); Bechara card task (DDT)	Heroin users scored lower on the STPI for future orientation, were less likely to predict future events and organize future events on the FTP, and were less likely to win money than controls.	Shortened time horizons and decreased sensitivity to delayed consequences could contribute to drug users' persistence use of drugs despite negative consequences.
Aleksandrov et al., 2005	Heroin-dependent individuals (n = 82) grouped by addiction duration and controls (n = 52)	Both groups administered time perception tasks, between-subject design.	Time interval task: 12-second interval perception, estimation, and reproduction	Heroin users estimated shorter time intervals as a group during withdrawal, then accurately after 5-6 days. Changes in subjective time perception related to addiction duration and interhemispheric brain asymmetry.	Heroin-dependent individuals show changes in subjective time course that may come from impaired subcortical rhythm-organizing formations and dopamine transmission.
<p>Table 3: Summary of original scientific articles included in the review that examine impulsivity and/or time perception in opioid use disorder. Only results regarding impulsivity and time perception or processing are reported in this table.</p>					

Article	Population Tested	Study Design	Tasks/Parameters	Main Results Concerning Impulsivity and/or Time Perception	Interpretation or Theory Proposed
Bickel et al., 2011	Treatment-seeking cocaine addicts (n = 47)	Subjects completed DDT tasks in different conditions. Between-group design.	Computerized DDTs with hypothetical monetary and cocaine rewards in different conditions: C-C, M-M, C-M, M-C	Cocaine addicts discounted delayed rewards more in the C-C vs. M-M condition, but the highest DD rates occurred in the M-C condition. Cocaine was discounted more at a delay than when immediately available.	Standard decision making models do not describe subjects' results. Possible that brain has two decision-making systems, one impulsive (drugs are valuable) and one executive (drugs less valuable), and balance between two is determined by drug availability.
Johnson et al., 2012	Cocaine-dependant individuals (n = 20), matched controls (n = 20)	Both groups underwent several DDTs. Efficacy of Quick Discounting Operant Task tested. Between-group analysis.	DDTs: Quick Discounting Operant Task with Coin delivery (QDOT); Experiential Discounting Task; DDT with real monetar rewards; DDT with hypothetical monetary rewards.	Cocaine group discounted at higher rates than controls on the QDOT, Experiential Discounting task, and hypothetical DDT.	QDOT an effective test; correlated with other DDTs and showed an effect between the cocaine and control groups.
Hoffman et al., 2008	Recently abstinent Methamphetamine (MA)-dependent patients (n = 19) and matched healthy controls (n = 17)	Subjects underwent fMRI and a DDT. Between-subject design.	fMRI scanning; computerized DDT with hypothetical monetary rewards	Difficult DD choices associated with greatest activation in bilateral middle cingulate, posterior parietal cortex (PPC), and right rostral insula. Control group showed more PFC activation than patients. Magnitude of discounting correlated with amygdala, DLPFC, posterior cingulate cortex, and PPC	Evidence for model wherein dorsal cognitive systems modulate neural response of ventral regions. Patients who prefer smaller immediate rewards over delayed rewards activate dorsal cognitive system to overcome preference. Amygdala activation to delayed rewards could suggest sensitivity to negative salience of delayed rewards.
Stevens et al., 2015b	Substance-dependent individuals (70 % cocaine users) in treatment (n = 70)	Subjects assessed with multiple cognitive self-report and behavioral tasks, and treatment outcomes evaluated.	UPPS; Stop Signal Task; IGT; computerized DDT with hypothetical monetary rewards	DD results and impulsive decision making predicted short-term relapse, an effect mediated by treatment retention.	Neurocognitive indices of impulsivity may be more sensitive to predicting relapse than trait-based self-report measures.

					Targeting processes involved in impulsive choice could reduce post-treatment relapse.
Stevens et al., 2015a	Substance-dependent individuals (76% cocaine users) in treatment (n = 84)	Subjects evaluated for treatment motivation and outcomes, as well as with DD measures.	Addiction-severity index; Motivation for Treatment (MfT) scale; Computerized DDT with hypothetical monetary rewards; analysis of treatment outcomes	High DD rates predicted shorter treatment retention and higher odds of prematurely dropping out of treatment. Effect of DD on treatment retention partially mediated by treatment readiness result.	Steep DD rates in drug users could become a clinically relevant behavioral marker. Targeting DD and treatment readiness could improve treatment retention in high risk patients.
Hulka et al., 2015	Cocaine users with decreased (n = 19), increased (n = 19), or unchanged (n = 19) cocaine intake after 1 year and healthy controls (n = 48)	Longitudinal study; cocaine users evaluated after 1 year and grouped into those that changed or maintained consumption. Assessed with self-report and behavioral cognitive tests at baseline and after 1 year.	BIS-11; Rapid Visual Processing task (RVP); IGT; computerized DDT with hypothetical monetary rewards	Cocaine increasers showed a trend for elevated BIS-11 scores, whereas decreasees showed reduced scores. Increasees improved on the IGT while decreasees deteriorated.	Self-reported and decision-making impulsivity covary with changing cocaine use and could monitor treatment success. DD did not change and could be potential endophenotype of stimulant addiction.
Ballard et al., 2015	MA-dependent individuals (n = 27) and healthy control group (n = 27)	Both groups completed the MCQ and underwent PET scanning. Between-subject design.	MCQ; Positron Emission Tomography	MA users showed steeper delay discounting and lower D2/D3 receptor availability. Discount rate was negatively correlated with D2/D3 receptor availability in combined sample and in MA group.	Evidence for link between deficient D2/D3 receptor availability and steep delay discounting, which fits with results showing low striatal D2/D3 receptor availability and higher risk of relapse in stimulant users.
Wittmann et al., 2007	Stimulant-dependent individuals (n = 15) and healthy controls (n = 15)	Both groups underwent series of timing tasks and were assessed for cognitive function. Cross-sectional design.	Duration discrimination; Temporal Reproduction; Paced Motor Timing; Time Estimation; Test for Attentional Performance battery; BIS-11	The stimulant-dependent group showed several abnormal time processing results; needed larger time differences for duration discrimination, accelerated finger tapping, and overestimated duration of a longer time interval (effect attributable to higher impulsivity)	Results show that substance-dependent individuals have altered time processing in several domains, one of which is explained by increased impulsivity. Altered time processing could be related to or explain difficulty delaying gratification in stimulant-users.

Table 4: Summary of original scientific articles included in the review that examine impulsivity and/or time perception in stimulants use disorder. Only results regarding impulsivity and time perception or processing are reported in this table.

Article	Population Tested	Study Design	Tasks/Parameters	Main Results Concerning Impulsivity and/or Time Perception	Interpretation or Theory Proposed
Heinz et al., 2013	Cannabis-dependent interested in self-quit (n = 72)	Subjects evaluated pre-cessation attempt and six months post-attempt on DD and drug use measures.	Marijuana Craving Questionnaire; Marijuana Motives Measure; University of Rhode Island Change Assessment; computerized DDT with hypothetical monetary rewards	Higher DD correlated with higher compulsive cannabis craving, earlier initiation of regular cannabis use, and seeking professional help for a previous quit attempt. DD did not predict cessation outcomes.	DD is sensitive to developmental trajectories of cannabis dependence, but does not predict cessation outcomes. Multimodal assessments of impulsivity are necessary for the study of cannabis use and outcomes.
Solowij et al., 2012	Adolescent cannabis users (n = 48), alcohol users (n = 65), and matched control non-substance users (n = 62)	All groups administered Information Sampling Test and assessed for drug use and history. Between-subject design, and within-group analyses.	The Information Sampling Test	Cannabis users had lowest degree of certainty before decisions on the task. Poor performance associated with earlier onset of regular cannabis use, and greater duration of cannabis exposure. Alcohol users did not differ from controls.	Increased risky and impulsive decision making (higher uncertainty levels, inefficient utilization of information) associated with adolescent exposure to cannabis.
Stanger et al., 2012	Adolescent cannabis users (n = 165) enrolled in clinical trial comparing treatments	Subjects completed a DDT at treatment onset. Within-subject analysis.	Computerized DDT with hypothetical monetary and cannabis rewards.	DD rates related to demographic variables like socioeconomic status and race. DD of \$1,000 predicted abstinence outcomes.	Could be important to determine adolescent cannabis users with high DD levels at treatment onset. This subgroup might require strategies that address impulsivity.
Lee et al., 2015	Individuals with cannabis use disorder seeking treatment: adolescents (n = 165) and adults (n = 104)	Subjects assessed with DDT at intake and end of treatment. Repeated measure mixed model design.	Computerized DDT with hypothetical monetary and cannabis rewards.	Adolescents less sensitive to changes in reward magnitude, discounted money at higher rates, and showed less improvement in DD rates over the course of treatment vs. adults.	Important to understand how development influences the impact of discounting on substance use in order to better design treatment.
Johnson et al., 2010	Cannabis-dependent users (n = 30), former cannabis-dependent users (n = 30),	All groups administered self-report and behavioral measures. Between-subject design and within-group analyses.	Computerized DDT for hypothetical monetary and cannabis rewards; EIS	Current cannabis-dependent users scored higher on impulsivity on the EIS, but groups did not differ on the BIS-11.	Results suggest that sense of powerlessness over the future is related to greater DD and that

	and matched-controls (n = 22)		(impulsiveness subscale); STPI; Future Time Perspective; BIS-11	STPI Present-Fatalistic subscale correlated with DD.	current cannabis dependence may be associated with DD.
Sewell et al., 2013	Frequent and infrequent cannabis users (n = 44)	Double-blind, placebo-controlled studies. Subjects received different doses of THC or placebo and underwent visual time estimation and production tasks in the seconds range three times on test days.	Time Estimation Task; Time Production task	All doses of THC induced time overestimation and underproduction, independent of dose. Chronic cannabis use did not affect baseline time perception. Infrequent users showed differences depending on dose, while frequent users did not.	A psychoactive dose of THC increases the internal clock speed as indicated by time overestimation and underproduction.
McDonald et al., 2003	Healthy adults that reported using cannabis ≥ 10 times (n = 37)	Double-blind placebo controlled within-subject design. Subjects received different doses of THC or placebo and completed multiple behavioral and self-report measures before and after drug administration.	Profile of Mood states; Drug Effects Questionnaire; End-of-Session Questionnaire; Digit Symbol Substitution Test; Hopkins Verbal Learning Test; Digit Span; Stop Task; Go/no-go task; computerized DDT and probability discounting task with hypothetical monetary rewards; BIS-11	THC increased impulsive responding on the Stop task but did not affect Go/no-go or DD or probability discounting. THC increased estimates of short interval durations but not longer intervals.	Results suggest that THC may augment certain impulsive behaviors but not others, and that impulsivity is made up of distinct components rather than a unitary process.
<p>Table 5: Summary of original scientific articles included in the review that examine impulsivity and/or time perception in cannabis use disorder. Only results regarding impulsivity and time perception or processing are reported in this table.</p>					

Article	Population Tested	Study Design	Tasks/Parameters	Main Results Concerning Impulsivity and/or Time Perception	Interpretation or Theory Proposed
Petry & Casarella, 1999	Substance using PGs (n = 29), substance using non-PGs (n = 34), and healthy controls (n = 18)	All groups assessed for drug use, addiction severity, and intelligence, then administered delay discounting task. Between-subject design.	Addiction Severity Index (ASI); South Oaks Gambling Screen (SOGS); Written DDT with hypothetical monetary rewards	In all groups, smaller rewards discounted more than larger rewards. Substance users had higher DD rates than controls, and substance-using PGs had higher rates than substance-using non-PGs.	Evidence of more rapid discounting of delayed rewards in substance users, especially with comorbid PG. Could be central feature to impulse control and addictive disorders.
Petry, 2001b	Substance-using PGs (n = 27), substance-using non-PGs (n = 63), and healthy controls (n = 21)	All groups assessed with self-report and behavioral measures. Between-subject design.	Stanford Time Perception Inventory (STPI); SSS; Eysenck Impulsivity Questionnaire (EIQ); BIS-11; Bechara Card Task	Substance abuse and PG status resulted in additive effects on impulse control and time orientation measures, and on preference for immediate gains on card task.	Association between substance abuse, PG, impulsivity, and time orientation.
Petry, 2001c	Pathological gamblers (PG) with substance use disorders (n = 21), without (n = 39), and controls (n = 26)	All groups completed self-report measures and DD task. Between-subject design.	ASI; SOGS; EIQ; Written DDT with hypothetical monetary rewards	PG group discounted delayed rewards at higher rates than controls, and PG with substance use disorders had the highest rates	Support for rapid discounting of delayed rewards as a feature central to impulse control and addictive disorders including PG
Alessi & Petry, 2003	PGs (n = 62)	Subjects assessed for addiction and substance abuse and completed DD task. Cross-sectional design.	ASI; SOGS; EIQ; Written DDT with hypothetical monetary rewards	SOGS and EIQ predicted a significant proportion of variance in subjects' individual DD rates; SOGS scores had the highest predictive value.	Gambling severity was the best predictor of impulsive behavior. Important to examine if increased impulsivity precedes or is subsequent to PG.
Dixon et al., 2006	PGs (n = 20)	Subjects assessed with DDT in an out of normal gambling context. Cross-sectional design.	Computerized DDT with hypothetical monetary rewards	16/20 subjects showed altered DD based on context; context-sensitive DD rates.	Evidence that DD rates are context sensitive; important to investigate variables that control temporal discounting in impulse control disorders.
Stea et al., 2011	Young adult sample (n = 218)	Subjects assessed for severity of gambling, cannabis, and alcohol. Completed DD task.	Computerized DDT with hypothetical monetary rewards; Problem Gambling Severity Index	Gambling problem severity accounted for DD scores most significantly	Gambling more associated with DD of hypothetical monetary rewards than other addictive disorders like substance use problems.
Hodgins & Engel, 2002	PGs (n = 20), Social gamblers (n = 22), psychiatric patients (n = 20)	All groups administered tests for gambling severity and time inventories.	Zimbardo Time Perspective Inventory (ZTPI), Future Time	PG group had shorter time horizons than social gamblers, but few differences between PGs and psychiatric patients.	Results suggest shortened time horizons in PG, but that this is not a unique feature of addicted

			Perspective Inventory (FPTI); SOGS		populations and psychological distress could be an explanatory variable.
Wiehler et al., 2015	PGs (n = 20) and matched healthy controls (n = 20)	Groups completed DD and episodic future thinking (EFT) assessments.	Computerized DDT with hypothetical monetary rewards; Autobiographical Memory Interview (for EFT) ; novel Time Perception task; Circle-size estimating task	Degree of non-linearity in time perception correlated with DD across groups. PG associated with increased DD and depression with decreased DD.	Results do not support idea that steep DD in PG is due to skewed time perception or EFT impairments.
Goudriaan et al., 2006	PGs (n = 49), Abstinent alcohol-dependent patients (n = 48); Tourette syndrome (n = 46), healthy controls (n = 49)	Cross-sectional study. All groups underwent neuropsychological and cognitive battery	SOGs; Stop Signal Task; Circle Tracing Task; Stroop Test; Time estimation and reproduction tests; Wisconsin Card Sorting Test; Controlled Oral Word Association Test; Self-Ordered Pointing task; Digit-Span test; Tower of London; Sorting Task;	PG and alcohol groups showed impaired performance on inhibition, time estimation, cognitive flexibility, and planning tasks.	Resemblance between PG and alcohol groups in executive function deficits suggest common neurocognitive aetiology for these addictive disorders.
Goudriaan et al., 2007	PGs (n = 46)	Group tested for self-report impulsivity, reward sensitivity, disinhibition, and decision-making.	Stop Signal Task; Stroop Test; IGT; Card Playing Task; BIS-11; BIS/BAS	Longer disorder duration, increased disinhibition and decision-making performance predicted relapse. Self-report impulsivity and reward-sensitivity did not.	Disinhibition, decision-making and disorder duration are powerful predictors of relapse in PG; could guide treatment planning.
Noseworthy & Finlay, 2009	Adults with gambling experience (n = 160)	Subjects gambled under different conditions. Between-subject and within-subject conditions.	Gambling (slot machines) with sound manipulations: typical casino auditory environment vs. music overlaid on typical casino sound, varied volume and tempo; Time estimation of elapsed play time	Typical ambient casino auditory environment promotes underestimations of elapsed duration of play. When music is introduced, durations reconstructed more accurately.	Ambient casino audio environment does not motivate temporal engagement, which implicates play-time. Music provides cue of interval, but not all music effective at conveying temporal cues

Table 6: Summary of original scientific articles included in the review that examine impulsivity and/or time perception in pathological gambling disorder. Only results regarding impulsivity and time perception or processing are reported in this table.

Addictive disorders	Global results on impulsivity in addictive disorder	Global results on time estimation in addictive disorder	Relationship between impulsivity and time estimation in addictive disorder
Tobacco use disorder	Increased impulsivity is correlated with higher dependence, relapse risk, and treatment outcomes	Overestimation of time during abstinence, craving and withdrawal	The relationship remains under-explored.
Alcohol use disorder (AUD)	Increased impulsivity correlated with the duration and severity of alcohol dependence	The literature on time estimation in AUD is very limited: toward an overestimation?	The relationship is not assessed
Opioid use disorder	Increased impulsivity has been shown to be correlated with heroin use duration and drug deprivation.	Overestimation of time but only during withdrawal periods; decreased sensitivity to delayed consequences and shortened time horizons.	The relationship remains under-explored
Stimulant use disorder	Increased impulsivity has been shown to be correlated with severity of drug use, short-term relapse, treatment outcomes and dopamine dysfunction and alteration in PFC.	Overestimation of time.	Relationship between overestimation of time and impulsivity but the nature of this relationship remains unexamined.
Cannabis use disorder	Increased impulsivity correlated with the precocity of use and greater exposure to cannabis.	Acute THC intoxication leads to an overestimation of time. No effect on time estimation was found in chronic cannabis users.	The relationship remains under-explored
Gambling disorder	Increased impulsivity correlated with severity of gambling and with the gambling context.	Distortion of time estimation in both sense.	The relationship remains unclear: some studies find results that can be interpreted as showing convergence between increased impulsivity and altered time perception: either subjects underestimated playtime or they overestimated intervals.

Table 7: General summary table that integrates the findings across substances/behaviors