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Beyond impulse control – toward a comprehensive neural account of future-oriented decision making

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ABSTRACT

The dominant focus of current neural models of future-oriented decision making is on the interplay between the brain's reward system and a frontoparietal network thought to implement impulse control. Here, we propose a re-interpretation of the contribution of frontoparietal activation to future-oriented behavior and argue that future-oriented decisions are influenced by a variety of psychological mechanisms implemented by dissociable brain mechanisms. We review the literature on the neural mechanisms underlying the influence of prospection, retrospection, framing, metacognition, and automatization on future-oriented decisions. We propose that the prefrontal cortex contributes to future-oriented decisions not by exerting impulse control but by constructing and updating the value of abstract future rewards. These prefrontal value representations interact with regions involved in reward processing (neural reward system), prospection (hippocampus, temporal cortex), metacognition (frontopolar cortex), and habitual behavior (dorsal striatum). The proposed account of the brain mechanisms underlying future-oriented decisions has several implications for both basic and clinical research: First, by reconciling the idea of frontoparietal control processes with construal accounts of intertemporal choice, we offer an alternative interpretation of the canonical prefrontal activation during future-oriented decisions. Second, we highlight the need for obtaining a better understanding of the neural mechanisms underlying future-oriented decisions beyond impulse control and of their contribution to myopic decisions in clinical disorders. Such a widened focus may, third, stimulate the development of novel neural interventions for the treatment of pathological impulsive decision making.

1. Introduction

Delay of gratification is often considered as a hallmark of self-control in intertemporal choice, the ability to resist the temptation of immediate rewards for the sake of higher-valued long-term goals. According to dual-systems accounts of self-control (Fudenberg and Levine, 2006; Hofmann et al., 2009; Metcalfe and Mischel, 1999), delaying gratification requires deliberative control processes inhibiting the impulse of giving in to the temptation of immediate rewards. Following such dual-systems accounts, prominent neural models of future-oriented decision making focus on the interactions between a frontoparietal control network and the neural reward system encoding the value of both immediate and delayed rewards (Frost and McNaughton, 2017; Smith et al., 2018; Wesley and Bickel, 2014). The idea of a competition between the networks involved in control processes and reward representation is very influential in clinical research on reward impulsiveness, and in line with this assumption frontoparietal control as well as dopaminergic reward regions show abnormal activity patterns in several clinical disorders with altered delay discounting (Chen et al., 2021; Owens et al., 2019). In substance dependence, for example, prefrontal hypoactivation during delay of gratification is commonly interpreted as evidence for impaired control processes (Chen et al., 2021; Owens et al., 2019). Prefrontal activation in intertemporal decisions also predicts the risk of smoking relapses in nicotine dependence, which again was considered as evidence for a contribution of control processes to impulsive behavior (Amlung et al., 2022). Similar interpretations were proposed for prefrontal hypoactivation during intertemporal choice in obesity (Weygandt et al., 2015; Zhang et al., 2022). Correspondingly, therapeutic neural interventions for the treatment of these deficits often target the prefrontal cortex as putative neural substrate of impulse control (Kekic et al., 2014; Mehta et al., 2024; Sorkhou et al., 2022; Wing et al., 2013). Crucially, these interpretations of altered

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prefrontal activation in clinical disorders are based on reverse inference and presuppose that the prefrontal cortex, and in particular the dorsolateral prefrontal cortex (DLPFC), indeed implements impulse control in delay of gratification.

While neural models focus on the interplay between frontoparietal regions and the neural reward system as putative neural implementation of impulse control, psychological accounts of intertemporal decision making highlight that, besides impulse control, several further psychological mechanisms can promote the achievement of long-term rewards (Ainslie, 2021; Fujita, 2011; Lades and Hofmann, 2019; Soutschek and Tobler, 2018). In these accounts, self-control is conceptualized as a result (obtaining long-term instead of short-term rewards) rather than a cognitive process (inhibition of temptation impulses), and we will adopt this definition of self-control here. According to Fujita, self-controlled behavior can also be achieved via regulating the availability of immediate rewards, automatization of behavior, and cognitive construal. Construal accounts, for example, explain the preference for immediate over delayed rewards not by a lack of impulse control but by more abstract mental representations of delayed relative to immediate rewards (Liberman and Trope, 1998; Trope and Liberman, 2010). However, because most reviews and meta-analyses on the neural basis of intertemporal decisions have predominantly focused on prefrontal control regions (Smith et al., 2018; Wesley and Bickel, 2014; Yang et al., 2018), a comprehensive overview about how these alternative self-control strategies are implemented in the brain is lacking. Moreover, the importance of impulse control for future-oriented decisions appears questionable from a psychological perspective, leaving open how exactly the DLPFC and associated brain areas contribute to future-oriented behavior. Here, we aim to fill this gap and to provide a comprehensive review of the neural mechanisms enabling self-controlled behavior, with a focus on self-control strategies beyond impulse control. For this purpose, we will first discuss existing neural models of intertemporal decisions and update the current view on how prefrontal regions implement delay of gratification. We will attempt to reconcile conflicting accounts on the role of the DLPFC for intertemporal decisions. Then, we go beyond the dominant focus on deliberative impulse control by reviewing the literature on brain mechanisms underlying alternative self-control strategies (Fig. 1) and by discussing the implications of the proposed neural account of intertemporal choice for both basic and clinical research.

2. Neural models of delay discounting

2.1. Brain regions involved in delay discounting

Meta-analyses provide converging evidence that delay of gratification in intertemporal choice correlates with activation in DLPFC, ventromedial prefrontal cortex (VMPFC), insula, the basal ganglia, parietal cortex, and the temporal lobe (Mattavelli et al., 2024; Owens et al., 2017; Smith et al., 2018; Wesley and Bickel, 2014). However, neural accounts of intertemporal choice disagree on the psychological and computational contributions of these regions to delay of gratification. Wesley and Bickel (2014) highlight the overlap between intertemporal decisions and working memory processes in a frontoparietal network, which is interpreted as indicator for an involvement of effortful control processes in intertemporal choice. In contrast to this, another account relates prefrontal activation to the representation of abstract information (Smith et al., 2018). This account claims the existence of an anterior-posterior axis for the coding of abstract information in the prefrontal cortex, whereby delayed rewards are considered as more abstract than immediate rewards, in line with construal level accounts of intertemporal choice (Fujita, 2011). Another approach is followed by Frost and McNaughton (2017), who subdivide the decision process into five components (sensory processing, representation of gains, value coding, imagination of delayed rewards, comparison between delayed and immediate rewards) that are claimed to be implemented by dissociable neural mechanisms. Here too, prefrontal activations are considered as representing abstract long-term goals. These models do not make strong claims regarding the dual-systems versus one-system controversy: According to dual-systems accounts, the neural reward system is more sensitive to immediate than to delayed rewards, whereas the DLPFC is thought to either represent delayed rewards or to be active independently of the choice made (Figner et al., 2010; McClure et al., 2004). In contrast, one-system accounts posit that the neural reward system represents the subjective values of both immediate and delayed rewards (Kable and Glimcher, 2007). These accounts can potentially be reconciled by the idea that DLPFC and the reward system (striatum) are more sensitive to delayed and immediate rewards, respectively, but the reward system encodes also delayed rewards and these representations can be strengthened via top-down control of the DLPFC over the reward system (Hare et al., 2014; van den Bos et al., 2014). Alternatively, it was also suggested that the reward system encodes the magnitudes of delayed rewards while DLPFC represents waiting time (Ballard and Knutson, 2009). We note that the different interpretations of prefrontal activation in intertemporal choice may not be mutually exclusive but highlight distinct aspects of working memory functioning, the passive storage of abstract information (Frost and McNaughton, 2017; Smith et al., 2018) or the active manipulation of working memory contents via control processes (Wesley and Bickel, 2014). This is in line with the hypothesized general role of DLPFC for voluntary control and in actively maintaining and integrating goal-relevant information (Miller and Cohen, 2001), which in the context of intertemporal choices includes long-term and short-term goals, reward values, or waiting costs. However, given that in these meta-analyses the conclusions are based on reverse inference, we will next discuss the evidence that speaks in favor of the idea that the DLPFC implements effortful control processes in intertemporal choice.

2.2. Brain mechanisms underlying deliberate control

Which neural evidence supports the notion that brain regions involved in deliberate, effortful control processes contribute to intertemporal decision making? While neuroimaging studies provided no coherent pattern on whether DLPFC activation differs between patient

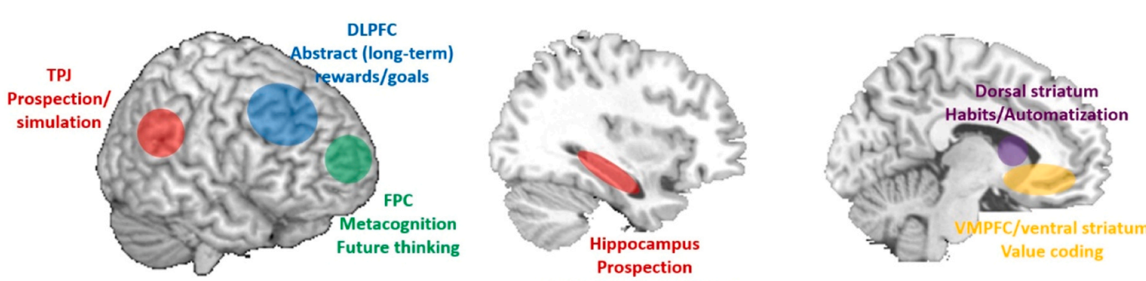

Fig. 1. Overview over brain regions involved in future-oriented decision making and the associated psychological processes.

and impulsive decisions (McClure et al., 2004; van den Bos et al., 2014), studies using transcranial magnetic stimulation suggest that inhibiting DLPFC excitability reduces choices of delayed compared to immediate rewards (Figner et al., 2010; Yang et al., 2018). Based on the assumption that choosing delayed over immediate rewards requires effortful impulse control (Metcalfe and Mischel, 1999) as well as the evidence for the DLPFC's involvement in control processes (Badre and Nee, 2018), these brain stimulation findings were taken as evidence that the DLPFC promotes delay of gratification via inhibiting the impulse to give in to the temptation of immediate rewards (Figner et al., 2010; Yang et al., 2018).

It is important to note, however, that control processes are not a unitary construct. A prominent psychological account distinguishes three subcomponents of control, and all of them were related to prefrontal activations: updating of working memory contents, inhibition, and shifting (Friedman and Miyake, 2017; Friedman and Robbins, 2022; Miyake et al., 2000). Conceptually, inhibition and working memory updating are plausible candidates for an involvement in intertemporal choice. However, there is increasing doubt that inhibitory impulse control contributes to intertemporal decisions (Bulley et al., 2022): Correlation studies provided little evidence for a link between delay of gratification and inhibitory control in response inhibition tasks or executive control tasks such as the Stroop or Simon task (Lange and Eggert, 2015; Scherbaum et al., 2018; Wilbertz et al., 2014). In contrast, patience in intertemporal choice correlates with working memory functioning (Hofmann et al., 2012; Kapetaniou et al., 2025b), which may be important for encoding long-term goals. Also on the neural level, DLPFC activation related to demanding working memory processes was enhanced for patient relative to impulsive decisions particularly for difficult decisions (i.e., decisions where the delayed and immediate reward are close in subjective value) (Jimura et al., 2018). Thus, behavioral and neural evidence suggests that the DLPFC promotes patience via representing and updating the value of long-term goals in working memory rather than by inhibiting prepotent impulses. This is further evidenced by the interactions between the DLPFC with regions belonging to the brain's valuation system, including VMPFC and striatum (Hare et al., 2009; Hare et al., 2014; van den Bos et al., 2014). These regions are thought to encode the subjective values of both immediate and future rewards (Kable and Glimcher, 2007), though we note that the precise role of the neural reward system in intertemporal decisions is still a matter of debate (Le Houcq Corbi and Soutschek, 2024; Soutschek et al., 2023; Soutschek and Tobler, 2023; Westbrook and Frank, 2018). Further, functional coupling between DLPFC and the valuation system strengthens neural representations of delayed relative to immediate reward values (Hare et al., 2009; Hare et al., 2014; van den Bos et al., 2014), supporting the view that DLPFC updates representations of abstract, delayed rewards. We note that ventral striatum and VMPFC as key nodes of the neural reward system may have dissociable functional roles, with the striatum more strongly representing immediate than delayed rewards (Hariri et al., 2006; Jimura et al., 2013; McClure et al., 2004; Tanaka et al., 2020), and vice versa for the VMPFC (Ballard and Knutson, 2009; Jimura et al., 2013; Sellitto et al., 2010). Evidence from non-human animals supports the view that the striatum encodes (both delayed and immediate) reward values (Cai et al., 2011), in contrast to the orbitofrontal cortex in rodents (Roesch et al., 2006; Stott and Redish, 2014). Taken together, existing evidence suggests that, rather than implementing inhibitory impulse control, prefrontal cortex represents and updates abstract information like the value of long-term rewards in working memory during intertemporal decisions and modulates subjective reward values in the reward system. In the following, we will argue that this idea can also be reconciled with construal-level accounts of intertemporal choice.

3. Neural mechanism of self-control beyond impulse control

3.1. Cognitive construal in DLPFC and beyond

At the very core of intertemporal decision making is the assumption that people's choices depend not only on the objective features of the environment but also on the subjective value people assign to different rewards, goals, and waiting costs. This links intertemporal choices to construal theory, whose central tenet posits that people's experiences and behavior are determined by their subjective interpretation ("construal") of the environment (Balcetis and Dunning, 2006; Henderson et al., 2011; Trope and Liberman, 2010). Events in the far future are considered to be construed on a higher level of abstraction than events in the close future (Liberman and Trope, 1998; Trope and Liberman, 2003). From this perspective, there are two ways to promote delay of gratification: first, to make immediate, short-term rewards less concrete, and second, to make long-term goals less abstract.

The relative attractiveness of immediate rewards can be modulated via framing effects. While immediate rewards are often presented in a hidden-zero format (e.g. "5 euro now"), explicit-zero formats ("5 euro in 0 days") were found to reduce delay discounting via lowering the attentional bias towards immediate rewards (hidden-zero effect) (Magen et al., 2008; Radu et al., 2011). This is supported by neural findings of weaker representations of immediate rewards in the striatum during explicit-zero compared with hidden-zero frames, suggesting that explicit-zero framing reduced the attractiveness of immediate rewards via lowering their relative concreteness compared to delayed rewards (Magen et al., 2014). Interestingly, explicit-zero versus hidden-zero framing also reduced DLPFC activation related to choices of delayed versus immediate rewards, which was interpreted as lower demand for impulse control processes (Magen et al., 2014). However, if we abandon the idea that delay of gratification relies on impulse control, an alternative interpretation of the lower DLPFC activation would be that explicit-zero framing reduces the relative level of abstraction of delayed compared with immediate rewards, which diminishes the demands on abstract goal representations in prefrontal cortex.

Delayed rewards can also be rendered more concrete by prospection and retrospection. Prospection is the ability to vividly imagine future events (Schacter et al., 2017; Szpunar et al., 2014). As future events (and thus rewards in the future) are thought to be more abstract than events in the present (like immediately available rewards), a strategy for increasing the appeal of future rewards is to make the time point of their delivery more concrete. In fact, replacing abstract information about reward delays with concrete events in the future (so-called prospective memory cues) reduces delay discounting (Daniel et al., 2015; Liu et al., 2013; Peters and Buchel, 2010). On the neural level, intertemporal decisions with prospective memory cues correlated with activation in hippocampus, amygdala, parietal cortex, DLPFC, and dorsal anterior cingulate cortex (ACC) (Peters and Buchel, 2010; Sasse et al., 2015). The hippocampus might contribute to constructing vivid imaginations of future events based on representations of long-term memory contents (Andelman et al., 2010; Hassabis et al., 2007; but see Squire et al., 2010). We note that hippocampus may influence intertemporal decisions not only via prospection but also via representing past reward experiences (Edelson and Hare, 2023; Shintaki et al., 2024; Tanaka et al., 2020), though here we mainly focus on the neural mechanisms underlying prospection. Moreover, episodic memory cues (which should, if anything, reduce rather than increase the need for inhibitory control) strengthen representations of future reward values in regions belonging to the frontoparietal control network like parietal lobe, DLPFC and ACC (Peters and Buchel, 2010). This is consistent with the idea that prefrontal regions encode the value of abstract rewards and goals in intertemporal choice. Other lines of research related future-oriented decisions to the temporo-parietal junction (TPJ) (O'Connell et al., 2018; Soutschek et al., 2016), and perturbation of TPJ activation reduced patient decisions by weakening neural representations of delayed rewards both in the striatum and the DLPFC (Soutschek et al., 2020). These findings are consistent with the TPJ's ascribed role for simulating future events (Arzy et al., 2009; Arzy et al., 2008), which should increase the value of future rewards by making them more concrete. These findings moreover suggest that brain regions involved in prospection influence intertemporal decisions even in the absence of explicit cues for future events, suggesting that decision makers spontaneously simulate the future when making intertemporal decisions, with these simulations strengthening representations of abstract rewards in prefrontal cortex.

Intertemporal choices were found to be susceptible not only to prospective but also to retrospective memory cues: Reminding decision makers of positive (but not negative) autobiographical events reduces delay discounting (Lempert et al., 2020; Lempert et al., 2017). On the neural level, intertemporal choices after autobiographical memory cues were associated with increased activation in the neural reward system and the TPJ (Lempert et al., 2017) and with greater cortical thickness in medial temporal lobe (Lempert et al., 2020). While the effects of retrospective memory cues on intertemporal choices are far from understood, the neural findings suggest that positive memories may affect the simulation and representation of future rewards, similar to future event cues. Taken together, the construal process of making delayed rewards less abstract involves interactions between brain regions related to episodic memory and mental simulations with the neural reward system as well as the frontoparietal control network.

The studies discussed so far focused on construal as a process, in particular the influence of framing or memory cues on the computation of the subjective values of future relative immediate rewards. But are the brain regions involved in construal in fact sensitive to the higher level of abstraction of delayed versus immediate rewards? Neuroimaging evidence indeed suggests that prefrontal activation relates to construal processes when evaluating distant versus proximate future events (Stillman et al., 2017; Tamir and Mitchell, 2011), and neural signatures of vividness, among others in the hippocampus and prefrontal cortex, weaken with increasing delay of future rewards (Lee et al., 2022). This further underlines the notion that brain regions sensitive to construal processes, including the prefrontal cortex, may be involved in representing the level of abstraction of future rewards.

How, then, can we reconcile the evidence for construal processes implemented by prefrontal regions with the idea that prefrontal cortex promotes delay of gratification via effortful control? Once we abandon the idea that the prefrontal cortex implements effortful impulse control in intertemporal choice but rather updates abstract information in working memory (as argued above), a window into construal level theories opens: contrary to theoretical claims that construal processes like prospection require no mental effort (Lempert and Phelps, 2016), empirical evidence suggests that simulating future events may require effortful working memory processes (Hill and Emery, 2013; Snider et al., 2018). This is consistent with recent findings according to which also other forms of mental simulations like social perspective taking are effortful and perceived as costly (Ferguson et al., 2020). We therefore suggest that the role of the prefrontal cortex, in particular the DLPFC, in intertemporal choice can best be explained by effortful construal processes that determine the relative concreteness of abstract contents like distant rewards and goals, and the concreteness of these prefrontal representations in turn may modulate subjective value representations in the brain's reward system. This may allow reconciling accounts according to which DLPFC implements patience either by effortful control or construal processes.

3.2. Regulating the availability of immediate rewards

Construal processes are not the only way to promote delay of gratification. When people are aware of their preference for short-term rewards like chocolate despite their goal of reducing overweight, they can avoid giving in to the temptation of chocolate by restricting their access to it, for example by having no chocolate at home. Such voluntary restrictions to one's access to immediate rewards are referred to as "precommitment" and are considered as an effective self-control strategy (Bryan et al., 2010; O'Donoghue and Rabin, 1999; Thaler and Shefrin, 1981). Other examples for precommitment entail the investment of savings for retirement in accessible funds (Laibson et al., 1998), setting costly deadlines for classwork (Ariely and Wertenbroch, 2002), or therapeutic interventions in substance dependence where the access to the desired substance is restricted (Bell, 2015; Standing and Lawlor, 2019). Theoretical accounts posit that the demand for precommitment arises from the risk of preference reversals (Bulley and Schacter, 2020; Kurth-Nelson and Redish, 2012; Laibson, 2015): Because people discount future rewards more steeply the closer in the future they will be available, people may reverse their preference for larger-later over smaller-sooner rewards if the delivery of the sooner reward becomes closer. In this case, it is beneficial to precommit to the later reward before one's preference switches to the sooner reward. Thus, precommitment requires metacognitive knowledge about how one's reward preferences change over time and the likelihood of preference reversals (Hennecke and Burgler, 2023). This implication is indeed supported by empirical findings of a link between metacognitive skills and the willingness to precommit. The demand for precommitment is highest in impulsive individuals (who are most prone to preference reversals), but deciding to engage in precommitment additionally requires that people have accurate metacognitive insight into their impulsiveness (Soutschek and Tobler, 2020). We note that metacognition is a broad construct with several facets, but here we refer with the term "metacognition" to the accurate knowledge about one's preferences (metacognitive accuracy). Based on these behavioral findings, one should expect precommitment to rely neurally on brain regions involved in metacognition.

In line with this hypothesis, voluntarily restricting one's access to immediate rewards is implemented by the frontopolar cortex (FPC) (Crockett et al., 2013; Soutschek et al., 2021; Soutschek et al., 2017; Wang et al., 2021), which was also ascribed a crucial role for metacognition in various domains of cognition (Fleming et al., 2014; Vaccaro and Fleming, 2018). Brain stimulation studies using different reward types and intertemporal choice paradigms replicated the causal link between FPC activation and precommitment (Soutschek et al., 2021; Soutschek et al., 2017; Wang et al., 2021). Interestingly, the FPC is functionally connected to DLPFC and VMPFC during precommitment decisions and metacognitive judgements (Crockett et al., 2013; De Martino et al., 2013; Kapetaniou et al., 2025a), suggesting that FPC may have access to information about the strength of the preference for delayed versus immediate rewards encoded in DLPFC and VMPFC when deciding whether or not to precommit.

While the focus of past research on the neural basis of precommitment was on the FPC, metacognitive processes were related also to other regions like DLPFC, VMPFC, DMPFC, precuneus and insula (Saccenti et al., 2024; Vaccaro and Fleming, 2018). Contrary to the FPC, however, these regions are thought to represent an individual's metacognitive bias (strength of subjective confidence) rather than metacognitive accuracy (Mattes and Soutschek, 2025; Shekhar and Rahnev, 2018; Vaccaro and Fleming, 2018). Nevertheless, a recommendation for future studies on precommitment is to overcome the focus on the FPC and to investigate whether also further regions involved in metacognition influence precommitment decisions.

The FPC, on the other hand, is involved not only in metacognition but also in prospective memory and episodic future thinking (Burgess et al., 2001; Schacter et al., 2017). Consistent with this, anterior parts of PFC were found to represent the values of anticipated future rewards (Jimura et al., 2013; Tanaka et al., 2020). From this perspective, the FPC's influence on precommitment might alternatively be explained by strengthened representations of future reward values. In this case, however, increasing FPC excitability should not only enhance the willingness to precommit but also result in more choices of delayed over immediate rewards independently of precommitment. Contrary to this prediction, past studies reported FPC stimulation to affect only precommitment decisions, but not intertemporal choices per se (Soutschek et al., 2021; Soutschek et al., 2017; Wang et al., 2021). We therefore speculate that different subregions of FPC may implement metacognitive accuracy versus episodic future thinking.

Metacognition was claimed to influence intertemporal decisions not only via precommitment but also by improving prospection (Bulley and Schacter, 2020). This implies that people with better metacognitive skills should generally make more patient decisions. While there is so far no evidence that metacognition generally predicts patience, metacognitive skills influence the susceptibility to framing effects (Bulley et al., 2022). Thus, better metacognitive knowledge of one's preferences implemented by the FPC may affect the achievement of long-term outcomes not only via precommitment but also by reducing the malleability of time preferences. These findings might be integrated into construal level accounts by assuming that better metacognitive knowledge of one's time preferences (implemented via information flow between FPC and prefrontal value representations) may counteract the concreteness advantage of immediate over delayed rewards.

3.3. Automatization

Automatization can foster the achievement of long-term goals without the engagement in effortful control or metacognition. For example, when a person formed the habit of eating healthy, she may no longer require effortful control to resist the temptation of unhealthy food; instead, the unhealthy food item may no longer be perceived as temptation at all. Furthermore, control processes can automatically be primed by cues in the environment: when I have learned that I need to resist the temptation of buying chocolate when standing in front of the sweets shelve, the sweets shelve might become a cue that automatically triggers control processes. While automatization was shown to reduce choices of short-term rewards in several domains (Fishbach et al., 2003; Papies et al., 2008), little is known about the neural mechanisms underlying automatization in intertemporal choice. In particular, no study so far investigated how forming the habit of choosing delayed over immediate rewards changes decision-related neural activation. A first glimpse into the neural underpinnings of habitual patience might be provided by groups habitually exerting self-control like anorexia nervosa. Anorexia nervosa is an eating disorder characterized by strict eating routines and habits (Seidel et al., 2022; Steinglass and Walsh, 2006; Uniacke et al., 2018). During intertemporal decisions, anorexia nervosa patients show enhanced activation in the dorsal striatum compared with control persons, even after controlling for differences in subjective values (Decker et al., 2015). This is consistent with the dorsal striatum's general role for habitual behavior (Graybiel and Grafton, 2015; Malvaez and Wassum, 2018). Another study related patience in anorexia nervosa patients (who showed no significant differences in delay discounting compared with healthy controls in this study) to activation in the ACC (King et al., 2016), a region involved in (among other processes) the allocation of effortful control (Shenhav et al., 2013; Soutschek et al., 2022b). Thus, studies on anorexia nervosa suggest that the striatum and the ACC may underlie habitual patience in intertemporal choice, though future research will have to clarify how exactly the process of habit formation changes neural activations underlying intertemporal choice.

A further line of research investigated the influence of incidental priming on the neural correlates of intertemporal choice, either using emotion-laden images (Morys et al., 2018) or religious cue words (Morgan et al., 2016). Negatively valenced cues resulted in flatter delay discounting in obese participants, which was accompanied by reduced activation in DLPFC (Morys et al., 2018). Religious priming did not affect choices between immediate and delayed rewards but accelerated decisions and enhanced functional connectivity between the striatum and the prefrontal cortex (Morgan et al., 2016). Taken together, preliminary evidence suggests that automatization of patient behavior is associated with stronger activation in the striatum and potentially also with lower activity in prefrontal cortex. Lower prefrontal activation related to habitual patience was interpreted as reduced demand for impulse control in past studies (King et al., 2016; Morys et al., 2018). However, based on the re-interpretation of prefrontal activation as proposed in this review, the lower prefrontal activation may instead reflect a reduced need for representing and updating delayed reward values in working memory.

4. Towards a comprehensive neural account of intertemporal choice

The goal of the current review is to overcome the focus on effortful control processes implemented in the frontoparietal control network, and specifically in the DLPFC, that is still dominating neuroscientific research on intertemporal choice. In line with psychological accounts (Ainslie, 2021; Fujita, 2011; Lempert and Phelps, 2016), we emphasize the richness of processes contributing to intertemporal decision making, which are also related to dissociable neural mechanisms. We propose that the DLPFC plays a central role in intertemporal choice not via implementing impulse control but by constructing and updating the subjective values of abstract future rewards in working memory. These representations interact with brain regions involved in value coding (striatum and VMPFC), imagining future events (hippocampus and TPJ), metacognition (FPC), and automatization of behavior (dorsal striatum) (Fig. 2). There are three major implications for basic and clinical research that follow from this account, as we outline in the following.

First, one must be cautious with drawing inferences from prefrontal activation to the involvement of effortful impulse control in intertemporal choice. While this fallacy is common in both basic and clinical research (Chen et al., 2021; King et al., 2016; Magen et al., 2014; Morys et al., 2018; Owens et al., 2019), there is actually little evidence for a contribution of inhibitory control processes to delay of gratification (Lange and Eggert, 2015; Scherbaum et al., 2018; Wilbertz et al., 2014). Moreover, prefrontal activations during intertemporal decisions were related to working memory and cognitive construal processes (Jimura et al., 2018; Peters and Buchel, 2010; Soutschek et al., 2020). Interestingly, construal processes like representing abstract future events were found to rely on working memory resources (Hill and Emery, 2013; Snider et al., 2018). We therefore propose that prefrontal activity during delay of gratification reflects effortful, working memory-dependent construal processes rather than impulse control. In turn, areas involved in prospection, metacognition, and automatization interact with these prefrontal areas to implement future-oriented behavior. We consider this account as a fruitful hypothesis that requires further empirical testing, for example by assessing the hypothesized effortfulness of construal processes in intertemporal choice. Moreover, it should become clear that interpreting prefrontal activity as neural substrate of impulse control, in basic research and clinical studies, represents a reverse inference fallacy. For example, the relationship between lower prefrontal activation during intertemporal choices and a higher risk of smoking relapses should not be considered as evidence for an involvement of impulse control processes but that stronger prefrontal representations of future rewards improve the resistance to smoking lapses (Amlung et al., 2022). While previous theoretical accounts on the neural basis of intertemporal choice disagreed on whether the DLPFC reflects working memory or construal processes (Frost and McNaughton, 2017; Smith et al., 2018; Wesley and Bickel, 2014), we provide a unifying account that integrates these ideas by proposing that prospection requires the representation and updating of abstract information in working memory-related prefrontal regions.

Second, highlighting the variety of psychological and neural mechanisms contributing to delay of gratification may lead to a better understanding of altered impulsiveness in clinical disorders. For example, it is known that substance dependence is associated with deficits in future orientation (Sansone et al., 2013) and with poorer metacognitive skills (Moeller et al., 2024; Soutschek et al., 2022a), and these

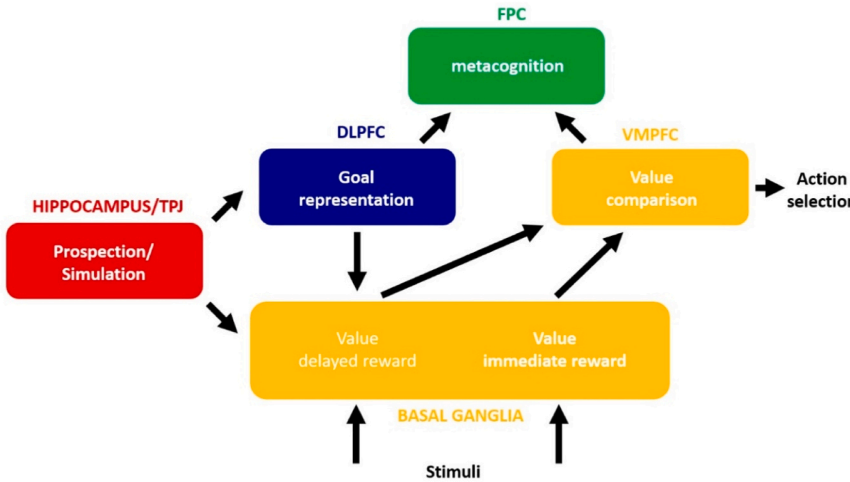

Fig. 2. Proposed interplay between the psychological processes underlying intertemporal decision making and their neural substrates. We note that the hippocampus and the FPC might influence intertemporal decisions also via further psychological mechanisms: The FPC was ascribed a role also for prospective memory and encoding future reward values, whereas the hippocampus might affect decision making by retrieving past reward experiences.

metacognitive deficits may contribute to impulsive behavior in substance dependence (Hamonniere and Varescon, 2018; Spada et al., 2015). In contrast to this, the neuroscientific research on substance dependence mainly focused on altered brain activation in the reward system and the prefrontal network, although there is evidence for altered activation also in regions belonging to the default mode network that play a role for prospection (Owens et al., 2019). Strengthening the focus on further brain regions beyond the fronto-striatal network may improve the understanding of how various neural mechanisms like prospection, metacognition, or automatization contribute to dysfunctional intertemporal choices in clinical disorders.

Third, the proposed framework may stimulate the development of novel neural interventions for the treatment of pathological impulsiveness. Current brain stimulation-based treatments of impulsive decision making focus almost exclusively on the DLPFC, but meta-analyses suggest these treatments to show only small-to-moderate effects (Mehta et al., 2024; Sorkhou et al., 2022). The relatively small effect sizes might not be surprising if not only alterations in prefrontal activation but also in other brain regions (associated with distinct psychological functions) contribute to impulsiveness in clinical disorders. Particularly non-responders to DLPFC-targeted treatments may therefore benefit from alternative stimulation targets like hippocampus, TPJ, or FPC depending on the neural origin of the impulsiveness deficits in an individual, in line with the goals of personalized psychiatry (Manchia and Carpiniello, 2018).

While this review aimed to paint a more comprehensive picture of the neural basis of intertemporal choice, several important questions remain open. First, decision making problems are often classified according to a hot versus cold dichotomy. Hot choice problems typically involve primary reinforcers (Schultz, 2015), whereas the intertemporal decision tasks discussed in this review mainly represent cold decision problems. It is still unclear whether dissociable neuro-cognitive mechanisms underlie hot versus cold decisions (Penolazzi et al., 2012; Pripfl et al., 2013), but we posit that in both hot and cold decisions the DLPFC updates the value of delayed rewards. Second, it is worth discussing whether DLPFC relates to state self-control (exertion of self-control in choice situations involving a conflict between immediate and delayed rewards) or trait self-control (general preference for delayed over immediate rewards). On the one hand, there is evidence for increased DLPFC activation during choices of delayed over immediate rewards if the choice options are close in subjective value (Jimura et al., 2018), speaking for a contribution to state self-control. On the other hand, DLPFC was both functionally and structurally related to individual differences in trait delay discounting (Koban et al., 2023; van den Bos et al., 2014), though conflicting evidence from a large sample study reported only the inferior frontal cortex, not the DLPFC, to correlate with trait self-control (Takehana et al., 2024). While the role of the DLPFC for trait self-control is therefore still a matter of debate, our theoretical framework could in principle account for the contribution of the DLPFC to both trait and state self-control via positing the DLPFC to be involved in the representation and context-dependent updating of future reward values. Third, delay of gratification can be promoted by further strategies like choice bundling (Ashe and Wilson, 2020), but to the best of our knowledge no study so far has investigated the neural mechanisms underlying bundling. Lastly, the contribution of several regions like the insula or the parietal cortex are far from understood and gained little attention in research on intertemporal choice. The insula represents the saliency of events, for example of large rewards (Wang et al., 2015), whereas the parietal cortex is thought to belong to the frontoparietal control network, but so far there is no causal evidence for an involvement of these regions to intertemporal choice (Vural et al., 2024). Likewise, also the contribution of the orbitofrontal cortex (OFC) to intertemporal choice is far from understood. Lesions to the medial OFC as part of VMPFC were shown to increase impulsive decision making (Sellitto et al., 2010), consistent with the idea that medial OFC/VMPFC represents the value of delayed rewards and mediates the influence of the DLPFC on decision making (Hare et al., 2009; Hare et al., 2014). Evidence from transcranial direct current stimulation studies suggest that also the lateral OFC might causally be involved in patient decisions (Moro et al., 2023; Nejati et al., 2018), though these results should be taken with caution due to the low spatial resolution of tDCS. However, a causal role of the OFC for patience was also shown in animal studies (Miyazaki et al., 2020) and may be related to signaling the expectancy of obtaining delayed rewards (Schoenbaum et al., 2009). The OFC might thus represent an alternative target for therapeutic neural interventions in clinical disorders characterized by impulsive decision making.

Taken together, we propose a novel account of the neural mechanisms underlying intertemporal decision making. Working memory processes in the prefrontal cortex play a central role for representing and updating future-oriented goals and rewards in interaction with the neural reward system as well as regions involved in mental simulations and episodic future thinking. We moreover highlight the diversity of psychological processes contributing to successful delay of gratification, including prospection, retrospection, metacognition, and habitualization, which are implemented by dissociable brain regions that interact with the prefrontal cortex and reward system. This account may contribute to a better understanding of the brain mechanisms underlying future-oriented decisions in healthy and clinical populations and inspire the development of novel brain-targeting therapeutic interventions for clinical impulsiveness.

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