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Temporal Cognition, Impulsivity and Intertemporal Choice

1. Introduction

Temporal cognition refers to the processes relating temporal characteristics of the physical world to the subjective experience of time.[1] Time is an essential and pervasive dimension in virtually all aspects of cognition and behaviour. Much of our thought, experience and behaviour is anchored in time, ranging from the recollection of past memories via present experiences such as pain or boredom, to plans and expectations about the future.[2] Neurophysiological studies have failed so far to identify a single brain region solely dedicated to our capacity for temporal cognition, in notable contrast with the functional specialisation of areas processing auditory or visual information. Instead, a number of brain structures are thought to process time-related information, such as hippocampus, striatum, insula, fronto-parietal cortex and cerebellum, and there are numerous theoretical models of how these areas and connectivity among them may represent time.[3]

One domain of cognition that is almost by definition highly sensitive to aspects of time is decision making. Decision making refers to a set of perceptual and cognitive processes that unfold over time and result in the choice of one response or course of action over another (or several others). Decisions are usually evaluated with regards to the (subjective) consequences for the decision maker or others. Various scientific disciplines have contributed to our understanding of decision making, most prominently psychology, economics, neuroscience and philosophy. Within these interdisciplinary decision

1 Matthews & Meck 2016.
2 Droit-Volet & Meck 2007.
3 Wittmann 2013.

sciences, the cognitive and neural processes underlying decision making are frequently investigated in situations of risk or uncertainty, i.e., when the probability of obtaining an expected outcome is known (but not 0 or 1) or poorly specified, respectively.[4]

The temporal dimension inherent in the decision-making process has also been studied intensively.[5] Specifically, not only the decision-making process itself but also the consequences of one's decisions always unfold over time, thereby placing decision-making squarely in the domain of temporal cognition. Notably, depending on the specific situation, the consequences of one's decisions may be experienced almost immediately, within a few hundred milliseconds, such as in the decision where to look next,[6] or much later, after years and decades, as in the decision which profession to take up or which insurance scheme to invest in.[7]

One type of decision task that is particularly relevant in the context of temporal cognition is intertemporal choice.[8] Intertemporal choice tasks model situations, abundant in everyday life, in which people have to decide between rewards of different magnitudes which are available at different times in the future. One example is the decision whether to spend money on an immediately rewarding activity, such as a night out, or to save it towards a future, and potentially more rewarding activity, such as an overseas holiday. In a typical intertemporal choice task, participants choose between smaller rewards that are available sooner and larger rewards that are available later. In general, people prefer rewards that are available earlier over rewards of the same size but available at a later time, thereby devaluing future rewards. This cross-species phenomenon is known as temporal discounting, or delay discounting.[9]

A number of theoretical explanations have been suggested to explain temporal discounting, including reward- or value-based accounts, cognitive accounts (focussing on representations, cognitive control, and prospection), personality-based accounts and (perceived)

4 Pleskac et al. 2015.
5 Kalenscher & Pennartz 2008 and Read & Scholten 2017.
6 Noorani & Carpenter 2016.
7 Malkoc & Zauberman 2019 and Sutter 2014.
8 Frederick et al. 2002.
9 Ainslie 1975 and Frederick et al. 2002.

time-based accounts.[10] In this chapter, we focus on time-based accounts of temporal discounting, given that time perception itself and its effects on intertemporal choice have recently gained considerably in interest.[11] In doing so, we also explore the relationship between intertemporal choice and impulsivity, as impulsivity has been hypothesised to reflect altered perception of time[12] and given that the widely reported finding of increased temporal discounting in individuals with higher levels of impulsivity[13] may be mediated by individual differences in temporal processing.[14]

We will first introduce intertemporal choice tasks as a prototypical paradigm of temporal cognition. We will then review studies of the effects of temporal processing manipulations on discounting behaviour, such as designs involving episodic future thinking or framing of temporal information. Next, we will discuss explanations of the temporal discounting phenomenon that are based on temporal cognition rather than other aspects of cognition (such as risk preferences). Finally, we will summarise and discuss evidence on the interrelationships between temporal processing, intertemporal choice and impulsivity.

2. Fundamentals of Intertemporal Choice

In its most canonical form, intertemporal choice refers to the choice between a smaller reward that is to be received sooner and an alternative, larger reward to be received at a greater delay. Thus, both decision options have two attributes: reward size and delay. Examples include the Marshmallow Test (»Would you rather have one marshmallow now or two in 15 minutes' time?«)[15] and the so-called consumption-savings problem (»How much of my income or wealth should I consume now and how much should I save and consume more at a later date?«).[16]

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10 B. K. Kim & Zauberman 2009, Peters & Büchel 2011 and Zauberman & Urminsky 2016.
11 Zauberman & Urminsky 2016.
12 Paasche et al. 2019.
13 Keidel et al. 2021.
14 Paasche et al. 2019.
15 Mischel 2014, Mischel et al. 1989, Shoda et al. 1990 and Watts et al. 2018.
16 Choi et al. 2006, Hall 1988 and Modigliani & Brumberg 1954.

For most decision-makers, the two attributes of decision options in an intertemporal choice task induce a trade-off: larger rewards are typically preferred over smaller rewards and rewards received sooner are typically preferred over rewards received later, ceteris paribus. Research on intertemporal choice is concerned with the modelling of this trade-off and the factors that influence it.[17]

A central issue in negotiating the trade-off between reward size and delay is the (non-)commensurability of the two attributes—how to compare an increase in one unit of reward to a decrease in one unit of delay? Typically, a decision-maker's preferences for reward size and delay are inferred from their choices. The latter can be used to infer a ranking of different options that were available to the decision-maker, which is usually referred to as preferences. Under certain conditions, this ranking can be represented by a so-called utility function, a mapping of reward size and delay into utility.[18] Thus, a utility function transforms the individual attributes of decision options—reward size and delay—into a common unit. The assumption is that in a given decision situation, a decision-maker would choose the option with the higher utility.

A utility function allows comparing a unit of reward, say 1 Euro, received at some delay, with a reward of similar size received immediately. The conversion of a future reward into its immediately-received equivalent, using a utility function, is called discounting and the value of a future reward discounted to the present is referred to as present value. Presenting a decision-maker with a series of decisions involving choices between rewards received immediately and rewards of different sizes received at varying delays allows inference of the so-called discount rate, the rate at which the decision-maker discounts future rewards per unit of time. A higher discount rate implies steeper discounting, that is, stronger devaluation of future rewards. Discount rates are often considered to be a measure of impulsivity.[19]

Differences in temporal discounting can manifest not only in the discount rate, the degree of discounting per unit of delay, but also in the functional form of the discount (utility) function. Different functions, such as exponential, hyperbolic and quasi-hyperbolic functions,

17 Frederick et al. 2002.
18 Mas-Colell et al. 1995.
19 Keidel et al. 2021.

typically differ in the weight they assign to different delays.[20] An important discount function is the exponential discount function. As its name indicates, future rewards are discounted as an exponential function of time: the utility (or discounted value) today of a future reward is given by $R/(1+r)^t$, where R is the value of the future reward, r is the discount rate per unit of time and t is the delay. This function assumes that the utility of delaying receipt of a reward is compounded over time: utility of delaying does not only accrue from the initial reward but also from additional utility gained in intermediate periods. This is reflected in the exponential form of the discount factor (Fig. 1).

Empirical research has demonstrated that human intertemporal choices are better described by a hyperbolic discount function, where the utility today of a future reward is given by $R/(1+kt)$.[21] As the term indicates, this discount function assumes that utility only grows linearly over time. Compared with exponential discounting, a hyperbolic function discounts rewards more steeply at shorter delays and less steeply at longer delays. It can lead to so-called ›preference reversals‹: A person who prefers $20 received today to $30 received in three months may also prefer $30 received in one year and three months to $20 received in one year's time. Such behaviour is inconsistent with exponential discounting and is sometimes considered to be »irrational.«[22]

20 Frederick et al. 2002.

21 Kable & Glimcher 2007/2010.

22 Frederick et al. 2002.

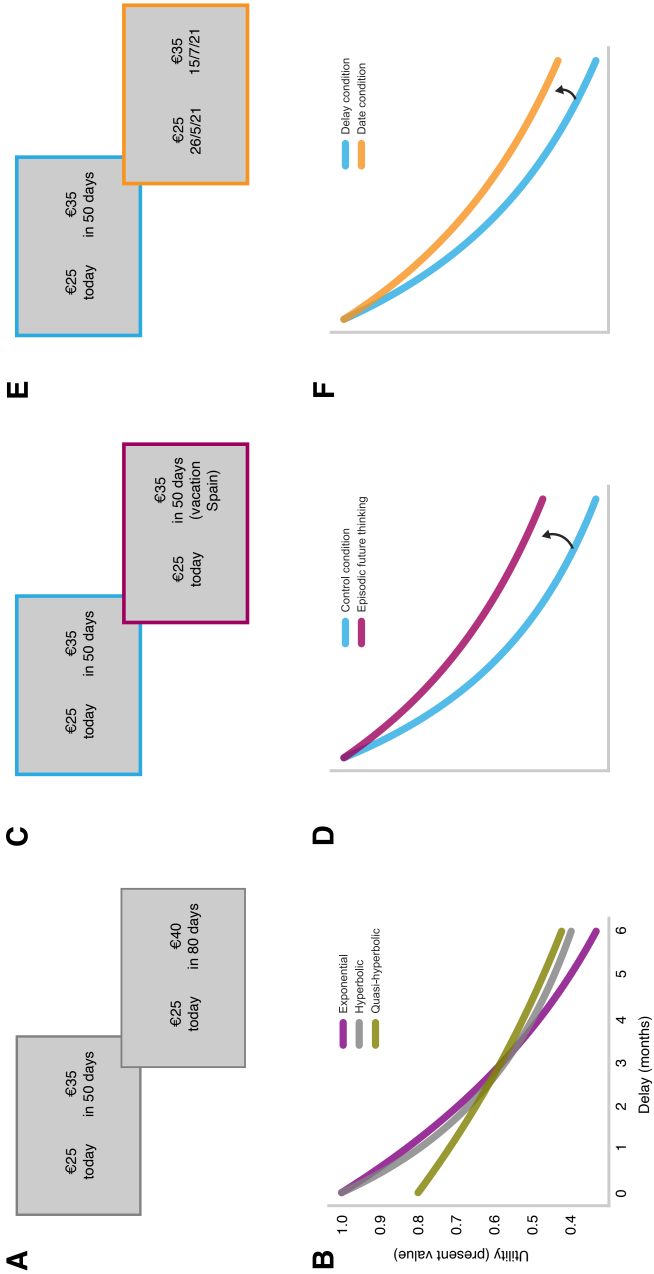

Figure 1: The Intertemporal Choice Task

Legend: (A) Examples of choices in an intertemporal choice task. (B) Different discount functions, mapping delay until a $1 reward is received into utility (present value). (C) Examples of choices in an intertemporal choice task investigating the role of episodic future thinking in temporal discounting. (D) Illustration of the effect of episodic future thinking condition on the discount function. (E) Examples of choices investigating the role of different ways of presenting delays in an intertemporal choice task. (F) Illustration of the effect of date vs. delay condition on discount function.

The discount functions discussed so far take as their arguments objective quantities, in particular, reward size and delay, and transform them directly into utility units, which in turn can be mapped into behaviour. Other approaches convert objective quantities into subjective values before mapping them into utilities. One motivation for the latter approach is to take properties of the perceptual system, e.g., number perception, into account when mapping stimulus properties (e.g., reward size, delay) into behaviour. A prominent example is the application of the Weber-Fechner law to interval timing in scalar expectancy theory,[23] which we discuss in more detail below. Other models take into account behavioural heuristics.[24] At this point, it is still an open question which factors determine the functional form of an individual's discount function.

Utility (or discount) functions have also been useful for identifying and characterising brain processes associated with intertemporal choice.[25] The parameters of these functions, in particular, the discount rate, can be estimated based on the choices a person makes, for example, in an intertemporal choice task. Subsequently, these functions can be used to compute the utility of individual decision options that a person is presented with. Brain imaging techniques such as functional magnetic resonance imaging (fMRI) have been used to locate brain areas and networks in which activation is correlated with the utility of decision options during intertemporal choice.[26]

This work has not only identified a network of brain regions associated with intertemporal choice but also structural and functional neural properties associated with individual differences in intertem-

23 Takahashi 2005 and Zauberman et al. 2009.

24 Lempert & Phelps 2016.

25 For recent reviews, see Frost & McNaughton 2017, Peters & Büchel 2011 and Schüller et al. 2019.

26 For meta-analysis, see Bartra et al. 2013.

poral choice.[27] The evidence so far suggests that certain structures and functional patterns in prefrontal, striatal, and subcortical brain regions associated with valuation, cognitive control, memory and future-oriented thinking, can, to some degree, account for individual differences in temporal discounting. It has been suggested that some of these structural and functional differences may serve as neural biomarkers of temporal discounting, that is, an objective biological measure of temporal discounting.[28]

3. Time-related Experimental Effects

The previous sections have highlighted the importance of temporal processes in decision making, in particular in intertemporal choice, both in theory and experimental design. This section will add to this notion by focusing on two influential experimental effects on intertemporal choice behaviour.

Generally, experimental manipulations in intertemporal choice paradigms can help to elucidate the psychological and neural mechanisms of intertemporal choice that lead to non-rational, hyperbolic discounting behaviour. Within the context of temporal cognition, research has aimed primarily at two different processes, namely the perception of outcome values at different points of time and the perception of time itself.[29] On the one hand, subjective valuation of objectively smaller, sooner and larger, later outcomes can be differentially influenced by visceral or emotional processes[30] or by cognitive representations of outcomes.[31] On the other hand, though possibly related, people are insufficiently sensitive to future time, and manipulations of time sensitivity can modulate intertemporal choice behaviour.[32] Specifically, Zauberman et al. showed that participants' subjective estimates of prospective time duration (marks on a line ranging from »very short« on the left end to »very far« on the right end) were not reflected by a linear function of objective time but by

27 Keidel et al. 2021.
28 Cho et al. 2013, Guo et al. 2017, Ikuta et al. 2018.
29 Ballard & Knutson 2009 and B. K. Kim & Zauberman 2009.
30 Loewenstein 1996.
31 H. Kim et al. 2013 and Malkoc & Zauberman 2006.
32 Ebert & Prelec 2007, B. K. Kim & Zauberman 2009, Zauberman et al. 2009.

its logarithmic transformation.[33] Interestingly, this is consistent with both hyperbolic discounting in intertemporal choice tasks and the Weber-Fechner law.[34]

Based on these important general findings, two specific experimental effects on intertemporal choice shall serve as examples to illustrate how manipulations of time-dependent valuation of outcomes or subjective time perception can influence intertemporal choice behaviour and, ultimately, reduce temporal discounting: episodic future thinking (EFT) effects[35] and the date/delay effect[36] (Fig. 1).

EFT is defined as the ability to simulate experiences of one's own future.[37] It plays a beneficial role in different cognitive and emotional functions including decision making, emotion regulation and spatial navigation.[38] In the context of intertemporal choice, EFT has been used to modulate discounting behaviour. In typical study designs, participants are first instructed to imagine and describe (positive) personal events at different points of time in the future. Subsequently, they complete a temporal discounting task in which the larger, later reward of each trial is cued by the self-generated event referring to that delay.[39] Although concrete induction methods of EFT (e.g., instructions) and control conditions (e.g., standard task without cues or cues referring to present/recent instead of future events) vary between studies, EFT has been shown to reduce temporal discounting relatively consistently and with moderate effect sizes.[40]

While the effectiveness of EFT in reducing temporal discounting is well documented, the underlying psychological mechanisms remain to be fully understood. Noël et al. and Rung and Madden summarize several possible and interconnected explanations.[41]

First, EFT effects can be interpreted in terms of construal-level theory,[42] according to which near future events are mentally represented as lower-level construals (more concrete) whereas events fur-

33 Zauberman et al. 2009.

34 Takahashi 2005, also see Dehaene 2003, who found that firing patterns of ›number neurons‹ follow the Weber-Fechner law.

35 Peters & Büchel 2010.

36 LeBoeuf 2006; Read et al. 2005.

37 Atance & O'Neill 2001.

38 Schacter et al. 2017.

39 Peters & Büchel 2010.

40 See Rung & Madden 2018 and Scholten et al. 2019 for reviews.

41 Noël et al. 2017 and Rung & Madden 2018/2019.

42 Trope & Liberman 2003.

ther into the future are represented as higher-level construals (more abstract). While this explains the so-called present bias, which puts a ›premium‹ on rewards received immediately,[43] in EFT, future rewards are rendered relatively more concrete and thus gain a comparable construal-level as immediate rewards, which facilitates option comparison and reduces temporal discounting.[44] This explanation is supported by the idea that better visualization abilities moderate EFT[45] and might also be linked to altered time perception (see below). Second, EFT might evoke an expanded temporal horizon,[46] which means that the time perspective in considering consequences of one's behaviour is shifted towards the future, possibly moderated by working memory capacity.[47] However, a recent study did not find extension of temporal horizon to be a mediator of EFT.[48] Third, given that humans' time sensitivity is often inadequate and strongly susceptible to manipulation,[49] time perception rather than time horizon may play an important role in EFT. For instance, it has been suggested that EFT may lead to enhanced attention to episodic events rather than time.[50] Thus, it could elicit lower sensitivity for duration until receipt of a larger, later reward, ultimately leading to less temporal discounting. Fourth, EFT manipulations that require the imagination of positive future events may enhance positive mood and thus indirectly strengthen cognitive control and working memory mechanisms.[51] In this case, the possibly moderating role of positive valence of EFT serves as important evidence.[52] Fifth, it has been argued that demand characteristics may drive EFT effects.[53] However, recent studies provided evidence against this notion.[54]

In sum, several non-exclusive mechanisms of EFT have been discussed and it is of course conceivable that several of these might combine to contribute to EFT effects. For instance, EFT, mediated by

43 Trope & Liberman 2003.
44 H. Kim et al. 2013, Rung & Madden 2018 and Yi et al. 2017.
45 Peters & Büchel 2010.
46 Lin & Epstein 2014 and Snider et al. 2016.
47 Lin & Epstein 2014.
48 Rung & Madden 2019.
49 Ebert & Prelec 2007.
50 Radu et al. 2011, Rung & Madden 2019.
51 Noël et al. 2017.
52 Liu et al. 2013.
53 Rung & Madden 2018.
54 Rung & Madden 2019 and Stein et al. 2018.

working memory mechanisms, may lead to more concrete positive future representations, which at the same time shift attention away from duration and enhance positive mood, resulting in less discounting behaviour. Future studies are required to separate these contributions in order to elucidate the psychological mechanisms of EFT effects in temporal discounting.

Another robust effect in the experimental intertemporal choice literature directly refers to time framing, namely, the date/delay effect.[55] In studies examining this effect, participants complete a temporal discounting task in which time until receipt of rewards is specified either as units of delay (e.g., 0 days vs. 23 days) or as dates equivalent in delay from the date of assessment (e.g., 1st of March 2021 (= today) vs. 24th of March 2021). The date condition has repeatedly been found to lead to a lower degree of temporal discounting than the delay condition, with moderate effect size,[56] both in studies using between-[57] and within-subject designs.[58] Interestingly, Read et al. also found this manipulation to reduce hyperbolic discounting,[59] i.e., decision making became more consistent with ›rational‹ behaviour specifying delays in terms of specific dates.[60]

Like EFT effects, the date/delay effect has often been replicated but the underlying mechanisms are not entirely clear, and several explanations have been offered.[61] First, like in EFT effects, construal-level theory has been drawn upon to suggest that the more concrete date framing might lead to a lower-level construal than delay framing (especially in larger, later rewards). This could make construal levels of choice options more similar, facilitate option comparison and thereby reduce temporal discounting.[62] Second, while delays and rewards are presented as continuous numeric variables, thus enabling a direct computational strategy (i.e., estimating exchange rates), presenting delays in terms of dates requires additional cognitive operations. For example, dates would either need to be transformed into delays to

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55 LeBoeuf 2006 and Read et al. 2005.
56 See Rung & Madden 2018 and Scholten et al. 2019 for reviews.
57 E.g. Read et al. 2005.
58 E.g. Dshemuchadse et al. 2013, though see Lempert et al. 2016.
59 Read et al. 2005.
60 See DeHart & Odum 2015, however, who found that hyperbolic/hyperboloid models provided a better description of choices.
61 E.g. Rung & Madden 2018. For additional approaches see LeBoeuf, 2006 and Read et al. 2005.
62 H. Kim et al. 2013.

perform computations or people might generally change their cognitive strategy, for example, by deciding primarily based on reward magnitude, which is considered more important.[63] Third, and relatedly, the date condition may lead to attentional shifts away from durations towards the reward attributes and their difference,[64] which increases the relative importance of reward values and diminishes the role of delay for choices (lowered time sensitivity). Fourth, estimates of time duration may be reduced with dates in comparison to delays because they are more concrete.[65] Indeed, both Zauberman et al. and Jiang and Dai showed that dates led to lower subjective estimates of objective time than delays.[66] Fifth, risk perception, which is partly confounded with temporal discounting,[67] might also be altered by dates in comparison to delays: Uncertainty of receiving rewards might be higher with delays than with concrete dates,[68] possibly as a consequence of differences in time perception.[69] Sixth, subadditivity (i.e., subdivision of elements into units, which are evaluated individually instead of in their entirety) increases discounting behaviour[70] and might also contribute to the effect because only delays (and not dates) can directly be subdivided into units.[71] Seventh, a date could be emotionally valued with stronger positive valence than a delay, as it focuses less on duration and is more concrete, eliciting positive mood and thereby causing less discounting (LeBoeuf, 2006; Lempert et al., 2016).

Again, some of these explanations could be integrated. As argued above, the date condition is more concrete than the delay condition, i.e., may reflect a lower-level construal. This in turn might lead to differential perceptions of durations and risk, general shifts in attention towards the rewards, or changes in strategy, causing higher valuation of rewards and less time sensitivity. Additionally, a more positive (or rather less negative) valence of duration and better mood might be elicited when dates are specified. As a result, people engage in less

63 Read et al. 2005.
64 Dshemuchadse et al. 2013 and Read et al., 2005.
65 Jiang & Dai 2021, Lempert et al. 2016, Read et al. 2005 and Zauberman et al. 2009.
66 Zauberman et al. 2009 and Jiang & Dai 2021.
67 Lopez-Guzman et al. 2018.
68 DeHart & Odum 2015, Jiang & Dai 2021.
69 Jiang & Dai 2021.
70 Read 2001.
71 DeHart & Odum 2015, however, see LeBoeuf 2006: Experiment 5 and Read et al. 2005: Experiment 1.

temporal discounting. Future studies will need to examine whether such an integrative explanation or only specific parts of it apply.

It should be noted that both the EFT and the date/delay effect may have direct implications on our daily lives. For example, they could be used in persuasion strategies in politics (e.g., conveying a better picture and creating better acceptance of energy-efficient measures by inducing EFT or speaking of specific dates) or offers of investments and saving schemes (e.g., engaging in EFT of a wealthy future, referring to specific dates on which profits are returned).[72] Importantly, given that temporal discounting is increased in a number of mental disorders,[73] these manipulations could possibly be integrated into psychotherapy settings in order to reduce impulsive choice behaviours. For instance, EFT has been shown to be an effective intervention in reducing both obesity[74] and cigarette smoking.[75]

In conclusion, EFT effects and the date/delay effect represent two important experimental effects in the intertemporal choice literature that illustrate how aspects of time influence temporal discounting behaviour. These manipulations not only improve our understanding of the cognitive and neural mechanisms underlying intertemporal choice but may also be used to optimize strategies in daily life and therapeutic contexts.

4. Intertemporal Choice, Temporal Processing and Impulsivity

Intertemporal choice and the role of temporal processes in temporal discounting has not only been studied using experimental or framing manipulations. There also exists a large literature on individual differences in intertemporal choice.[76] In this section, we turn to a particular trait correlate of temporal discounting, namely impulsivity. Specifically, we will first turn to time-relevant aspects of impulsivity and will then explore the role that sensitivity to temporal information might play in the often-reported relationship between intertemporal choice and impulsivity.

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72 LeBoeuf 2006 and Read et al. 2005.
73 Amlung et al. 2019.
74 Sze et al. 2017.
75 Stein et al. 2016/2018.
76 For review, see Keidel et al. 2021.

Impulsivity is a broad and rather poorly specified term that has been defined most generally as »a predisposition toward rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions to the impulsive individual or to others«.[77] Theoretical criticisms of the very construct of impulsivity aside,[78] impulsivity is widely studied in psychology, psychiatry and neuroscience. Impulsive symptoms, traits and behaviours can be assessed with clinical diagnostic instruments, psychometric personality inventories and experimental tasks, respectively.[79] However, correlations between these different levels of measurement are typically low,[80] likely reflecting the heterogeneity of the impulsivity concept.[81]

Theoretical models of impulsivity generally accept the heterogeneity of the construct, but differ with regards to the number and nature of dimensions they postulate. For example, in one of the historically most influential conceptualisations and assessments of impulsivity, Barratt distinguished between attentional impulsiveness (such as difficulties in focussing on a task at hand and suppressing distracting thoughts), motor impulsiveness (such as acting on the spur of the moment or having an inconsistent lifestyle) and non-planning impulsiveness (such as a low tendency to think ahead carefully or engage in challenging mental tasks), resulting in the Barratt Impulsiveness Scale.[82] Another widely adopted psychometric model and questionnaire is the UPPS Impulsive Behavior Scale by Whiteside and Lynam.[83] The original UPPS contains four dimensions, namely, negative urgency (the tendency to act rashly during intense negative affect), lack of premeditation (the tendency to act without thinking), lack of perseverance (the tendency to be distracted and give up on boring or difficult tasks) and sensation seeking (the tendency to seek new and exciting experiences). Lynam et al. later added the positive urgency dimension (the tendency to act rashly during intense positive affect), thereby creating the UPPS-P Impulsive Behavior Scale which

77 Moeller et al. 2001: 1784.
78 Strickland & Johnson 2021.
79 MacKillop et al. 2016 and Sharma et al. 2014.
80 Aichert et al. 2012 and Cyders & Coskunpinar 2011.
81 Evenden 1999.
82 Patton et al., 1995.
83 Whiteside & Lynam 2001.

has since been used and validated in numerous studies.[84] It should be noted that other models and measurements of impulsivity have also been proposed.[85]

Findings from intertemporal choice tasks are often interpreted within an impulsivity framework in mind,[86] and temporal discounting is sometimes explicitly regarded as a behavioural measure of impulsivity in both humans and non-human animals.[87] Evidence for this interpretation comes inter alia from large-scale studies of healthy individuals, showing that individual differences in self-report, psychometric impulsivity are consistently albeit weakly associated with temporal discounting.[88] Further support comes from studies of patients with clinical disorders that are known to involve impulsive symptoms, such as drug abuse or attention deficit hyperactivity disorder (ADHD). Numerous studies have provided evidence that those disorders are reliably characterised by increased temporal discounting.[89]

Of particular relevance to this chapter is the observed association between intertemporal choice and impulsivity, albeit of small magnitude,[90] which has been explained theoretically with reference to models of time processing.[91] Specifically, both temporal discounting and impulsive actions may be interpreted as the choice of immediate, smaller gratification (with negative consequences) over delayed, larger gratification.[92] Indeed, the ability to delay gratification in time has been considered to be a hallmark feature of self-control,[93] and impulsive behaviour is often conceived of as the opposite of self-control.[94]

To illuminate the role of time processing in impulsivity and in the relationship between impulsivity and temporal discounting, theoretical models of how objective time flow is subjectively perceived should first be considered. Several such models exist.[95] An influential, early model is that by Treisman, who proposed an ›internal clock‹

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84 Lynam et al. 2006.
85 Dickman 1990 and Eysenck et al. 1985.
86 Peters & Büchel 2011.
87 Hamilton et al. 2015 and Scholten et al. 2019.
88 E.g. Keidel et al. 2022 and MacKillop et al. 2016.
89 Amlung et al. 2019.
90 Keidel et al. 2021.
91 Paasche et al. 2019 and Wittmann & Paulus 2008.
92 Paasche et al. 2019.
93 Mischel et al. 1989.
94 Rachlin & Green 1972.
95 For review see Matthews & Meck 2016.

mechanism based on the existence of pacemaker and accumulator units.[96] The pacemaker produces a series of pulses travelling along a pathway at a constant rate. Their number is recorded by a counter, or accumulator, with the number of pulses corresponding to temporal duration. An additional component is the attentional gate, with pulses counted only when attention is oriented towards the passing of time. Importantly, time sensitivity is not rigid but instead is subject to external and internal influences;[97] anecdotally, it is well known to us that time seems to pass very quickly when having fun but seems to extend endlessly in a state of boredom. These state influences on temporal processing can be explained by two mechanisms.[98] First, the production rate of the pacemaker has been postulated to increase with heightened arousal, leading to a greater number of pulses produced and thus the experience of a longer duration of time. Second, increased attention to time (as may happen in boredom, but which is unlikely to happen when one is engaged in a fun, attention consuming task) is similarly postulated to lead to a greater number of produced pulses and, thereby, a longer perceived duration.

Of relevance to the present discussion, it has been proposed that impulsive behaviour may result from altered time processing, specifically from an overestimation of the flow of time.[99] Thus, for a highly impulsive individual, a given time interval would subjectively feel longer than for a less impulsive person. For that reason alone, highly impulsive individuals may be expected to display greater temporal discounting, as a given delay interval would represent a higher cost against which the reward must be traded off than for those with less contracted time perception.

Evidence in support of this hypothesis comes from a number of sources. First, otherwise healthy individuals with higher levels of impulsivity have been observed to overestimate the duration of time intervals compared to less impulsive individuals.[100] Second, sleep deprivation, which has been shown to transiently induce impulsive behaviours and disinhibition,[101] has been found to cause both increa-

96 Treisman 1963.
97 Droit-Volet & Meck 2007.
98 Wittmann & Paulus 2008.
99 Wittmann & Paulus 2008.
100 Lawrence & Stanford 1998.
101 Anderson & Platten 2011, Kumari & Ettinger 2020 and Meldrum et al. 2015.

sed temporal discounting and alterations in timing task performance suggestive of faster subjective time experience.[102] Finally, patients with borderline personality disorder, drug dependence or frontal lobe damage show both impulsive behaviours and faster subjective time processing, and often associations between the two.[103]

In conclusion, there is evidence of interrelationships between heightened impulsivity, faster subjective experience of time and increased temporal discounting. Put simply, these associations may be interpreted to suggest that impulsive individuals show enhanced temporal discounting due to a faster subjective sense of time flow. However, it should be noted that the relationship between time processing and impulsivity is likely to be complex and has not yet been fully understood. Specifically, the reasons for faster subjective time experience in people with high levels of impulsivity remain unclear, with both a faster pacemaker and enhanced attention to time as well as interactions amongst them postulated as explanations, whereas impaired inner clock mechanisms per se are considered less likely.[104] It should also be noted that the overlap between psychometric, self-report impulsivity and temporal discounting is of small magnitude,[105] suggesting that substantial variance in either measure remains unexplained by a postulated, shared alteration in temporal processing sensitivity.

5. Conclusions and Outlook

In this chapter, we focussed on intertemporal choice as a manifestation of temporal cognition. In particular, we introduced key methodological approaches and concepts in the study of intertemporal choice and provided an overview of both experimental and individual differences-based findings that relate intertemporal choice to aspects of temporal information processing.

With regard to experimental effects, we discussed framing effects in which temporal information processing is experimentally manipulated, namely, the episodic future thinking (EFT) and date/delay

102 Reynolds & Schiffbauer 2004.
103 Berlin et al. 2004, Berlin & Rolls 2004 and Wittmann et al. 2007.
104 Wittmann & Paulus 2008.
105 Keidel et al. 2021.

manipulations. The effects that result from those manipulations underscore the importance of temporal information processing in intertemporal choice. Specifically, both detailed thinking about specific, often positive future events and a change from the common expression of a reward delay as a time period to a specific date in the future cause reduced temporal discounting. These effects are well replicated in the experimental literature[106] and thus present an ideal starting point for further research into processes of temporal cognition that may underlie temporal discounting. Specifically, the specific psychological mechanisms underlying these effects remain unclear. Whilst a number of hypotheses have been put forward (see above), it remains unclear how exactly temporal discounting is affected by EFT and the date/delay manipulation—both at the psychological and the neural level.

Following our discussion of group-level effects of temporal manipulations on intertemporal choice, we summarised evidence that individual differences in temporal discounting, impulsivity and their association may to some extent be explained by inter-individual variation in sensitivity to time. Specifically, we followed the argument that both temporal discounting and impulsive behaviour may be viewed as choosing immediate, smaller gratification over delayed, larger gratification, and outlined the hypothesis that impulsive actions may result from an overestimation of durations. Within this framework, a highly impulsive person would experience a given time interval as longer than a less impulsive individual, which could underlie the observed, greater temporal discounting in highly impulsive individuals.

A number of caveats remain in this area of research. First and foremost, impulsivity is increasingly recognised as a poorly defined, heterogeneous construct,[107] necessitating careful consideration of which aspect of impulsivity is being investigated. Second, associations between impulsivity and intertemporal choice tend to be of only small magnitude, requiring samples with appropriate statistical power.[108] Third, the cognitive and neural mechanisms that underlie these associations remain to be characterised in more detail. More research is needed in this area.

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106 Rung & Madden 2018.
107 Strickland & Johnson 2021.
108 Keidel et al. 2021.

To conclude, intertemporal choice is a decision-making task that yields the widely reproducible, cross-species phenomenon of temporal discounting. The task can be placed firmly in the temporal cognition literature, and both group-level experimental effects and individual differences studies point to a substantial role of temporal perceptual and cognitive processes in intertemporal choice. More refined characterisation of the cognitive and neural mechanisms that underlie these findings is required in the future.

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