Opinion TRENDS in Cognitive Sciences Vol.xxx No.x

Full text provided by www.sciencedirect.com ScienceDirect

Decision making, impulsivity and time perception

Marc Wittmann[1,3] and Martin P. Paulus[1,2,3]

[1] Department of Psychiatry, University of California San Diego, La Jolla, CA 92093, USA
[2] Laboratory of Biological Dynamics and Theoretical Medicine, University of California San Diego, La Jolla, CA 92093, USA
[3] Veterans Affairs San Diego Healthcare System, San Diego, CA 92161, USA

Time is an important dimension when individuals make decisions. Specifically, the time until a beneficial outcome can be received is viewed as a cost and is weighed against the benefits of the outcome. We propose that impulsive individuals experience time differently, that is with a higher cost. Impulsive subjects, therefore, overestimate the duration of time intervals and, as a consequence, discount the value of delayed rewards more strongly than do self-controlled individuals. The literature on time perception and impulsivity, however, is not clear cut and needs a better theoretical foundation. Here, we develop the theoretical background on concepts of time perception, which could lead to an empirically based notion of the association between an altered sense of time and impulsivity.

Introduction

The perception of time is a crucial factor when individuals have to make decisions and consider the outcomes associated with their choices. Rewards that are received sooner are often preferred over future rewards, that is the subjective value of an outcome is discounted as a function of the delay [1,2]. It is well known that impulsive subjects devalue temporally delayed rewards more strongly than do comparison subjects, and this behavior might be due to their altered sense of time. According to this hypothesis, impulsive individuals will opt for smaller and immediate rewards more often than for delayed but higher rewards because they estimate duration as being subjectively longer than do more self-controlled individuals. The perception of time as lasting too long is associated with too high of a cost, which leads to the selection of alternatives with more immediate outcomes (see Figure 1).

Several empirical studies pointing to a possible association among impulsivity, decision making and time perception have been conducted over the last few decades [3–8]. However, only recently has this notion been addressed in a more systematic way. Here, we develop a conceptual framework that can guide current and future research and might allow researchers to build a consistent theory framing impulsivity, decision making and the experience of time. We will point to some methodological factors that have to be controlled for to reach valid conclusions and to explain impulsive decision making in inter-temporal choices. First, findings will be reviewed on impulsive behavior in inter-temporal choices, particularly in delay-discounting tasks, which examine the influence of time on decision making. Second, cognitive models of time perception will be related to study results showing that impulsive subjects display an altered sense of subjective time. It will be argued that the association between time perception and mood states plays a fundamental role in interpreting these empirical results.

Decision making and impulsivity

Every day we have to decide between options that have immediate or delayed consequences. For instance, we might restrict our eating habits to reduce our body weight, thereby opting for a momentary loss of pleasure associated with food to gain the future benefits of better physical health and appearance. Similarly, a student might have to decide whether to go to a party tonight or to stay at home and study for an exam that is scheduled tomorrow (the possible later higher reward is here, of course, to pass the exam). The process of deciding whether to opt for an immediate or earlier reward or for a delayed but higher reward is strongly related to scholarly and professional success in life [9]. To function effectively, one voluntarily has to postpone impulsive urges for immediate gratification and rather persist in goal-directed behavior to achieve positive outcomes in future [10].

Results from decision-making experiments show that people avoid risk when they have to choose between options associated with probable versus sure outcomes. Specifically, individuals choose a sure thing over rewards with a probabilistic outcome – even when the probabilistic alternatives have equal or even higher expected value [11]. The duration between the choice and the reception of the reward is another important factor that biases our decisions. A delayed outcome of a choice reduces the subjective value of the reward, a phenomenon called delay discounting [12,13]. Generally speaking, one prefers to receive rewards sooner rather than later. Future rewards are discounted such that they are worth subjectively less as a result of the delay. One way to measure temporal discounting behavior in human participants experimentally is by presenting individuals with a hypothetical or a real choice between two options, for example 'would you prefer $10 right now or $20 in a week?' In delay discounting procedures, participants make choices between rewards that are smaller but sooner versus rewards that are larger

Corresponding author: Wittmann, M. (wittmann@ucsd.edu).
Available online xxxxxx.

 1364-6613/$ – see front matter doi:10.1016/j.tics.2007.10.004

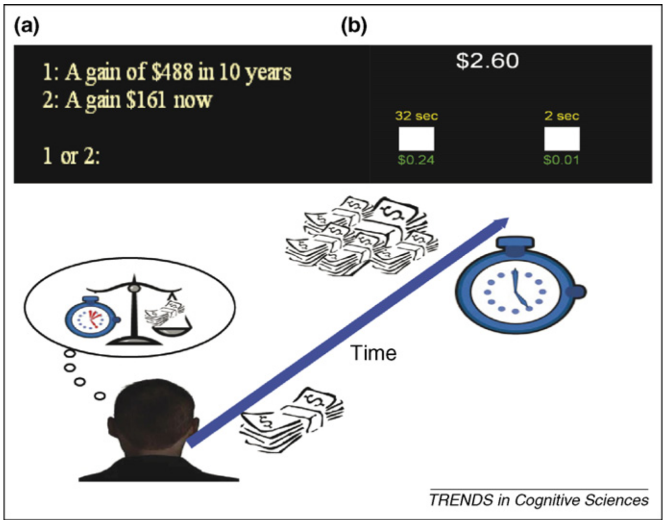

Figure 1. This figure shows two typical inter-temporal decision tasks. **(a)** In a hypothetical task, subjects are asked to decide between a smaller gain now and a higher reward in the future. Time scales for the delayed reward typically are varied from a few days up to decades [51]. **(b)** In a real task, subjects have to decide between a reward received within 2 s and larger rewards with delays of many seconds [14]. The actual money subjects can earn, based on their consecutive decisions, accumulates and is presented on the upper part of the screen. The lower illustration shows the degree to which an individual processes time as a cost in decision making. The internal representation of duration as the cost in time and the reward value are weighed against each other when choosing the immediate but smaller reward over the delayed but larger reward in the future.

but delayed (Figure 1). As the duration of the delay to the second option increases, preference for this option usually decreases. The temporal discounting pattern has repeatedly been described as following a hyperbolic function, meaning that after an initial steep decline of the subjective reward with increasing delays, even very remote outcomes retain some (albeit minute) value for the decision maker [1,14,15].

Individuals differ in how strongly they retain subjective value as a function of time. Moreover, the degree to which people are able to delay gratification is generally associated with the notion of willpower [16], whereas those who choose immediate gratification at the expense of important long-term interest are judged to be impulsive [1,17]. However, impulsivity is determined by a complex set of processes and consists of multiple components [18], and this contention is consistent with the finding that the correlations across different methods of assessing impulsivity are modest [19]. Nevertheless, impulsivity can be conceptualized as a pattern of behavior for which the potential of negative consequences has limited influence on the planning of actions. The external validity of using delay-discounting paradigms to quantify dysfunctions of impulse control is based on findings that children with attention deficit hyperactivity disorder (ADHD) [4], individuals with neuropsychiatric disorders [20], smokers [21], alcoholics [22] and substance-dependent individuals [23] show increased discounting of delayed rewards.

Despite the well-established finding that impulsive individuals discount delayed rewards more strongly than do more self-controlled individuals, the underlying cognitive and affective processes that account for this phenomenon are poorly understood. The decision-making processes associated with delayed discounting depend on neural substrates that are important for regulating emotions and feelings [16,24]. Functional imaging studies using delay discounting tasks are beginning to examine which brain areas are associated with impulsivity and self control (see Box 1). Findings from a different set of studies point towards the possibility that impulsive individuals have an altered sense of time [4–8,25], which might explain why they have difficulties in delaying gratification.

Cognitive models linking time perception and impulsivity

Experimental tasks that probe time-interval production and estimation

Although it is not yet clear how time keeping is implemented in the brain [26–29], several brain areas provide fundamental building blocks of an interval-timing system (a neural clock) for durations in the seconds range (see Box 2). Cognitive models, which assume that an internal clock with a pacemaker produces subjective time units [30], have been fairly successful in interpreting human time perception and animal timing behavior (see Figure 2). The subjective duration of time is defined by the number of temporal units accumulated over a certain time span. When individuals are asked to judge intervals of, for example, 30 s during a time-estimation task, an overestimation would correspond to an increased accumulation of temporal units over that period. In comparison, because of an increased accumulation of units over time, an individual would perform with a shorter production of the

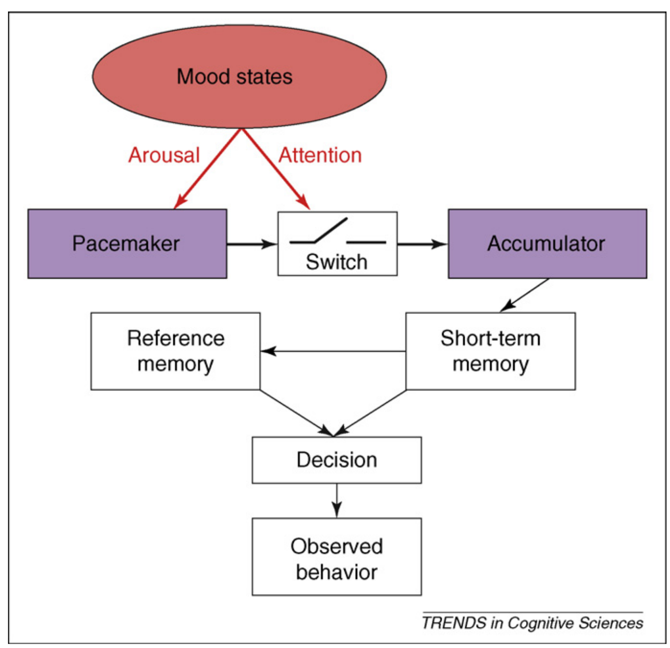

Figure 2. In cognitive models of time perception, a pacemaker produces a series of pulses that are fed into an accumulator. The number of pulses that has been recorded for a given time span represents experienced duration. The pulse number is compared with stored representations of time periods that can be verbalized (as seconds or minutes). Attentional gate models [30] assume that only when attention is directed to time pulses are accumulated. A switch is closed which then opens a gate to the accumulator. Two possible ways can be assumed for how mood states can influence the subjective experience of duration. Firstly, increased arousal leads to higher pacemaker rate and, thus, to a greater accumulation of pulses during a given time period. Secondly, increased attention to time leads to an increased inflow of pulses and, thus, also to their greater accumulation. The models of time perception contain multiple processing steps comprising a memory and a decision stage too [31].

Please cite this article in press as: Wittmann, M. and Paulus, M.P., Decision making, impulsivity and time perception, Trends Cogn. Sci. (2007), doi:10.1016/j.tics.2007.10.004

Box 1. fMRI studies on delay discounting

Functional magnetic resonance imaging (fMRI) studies have explicitly addressed impulse control using delay-discounting tasks and real rewards. Strong evidence of limbic and paralimbic cortical activation was found when subjects were presented with choices between a smaller earlier reward and a greater but delayed reward [54–56]. Lateral prefrontal and parietal cortices associated with executive control were activated when subjects delayed gratification, that is when they chose the delayed reward [54–56]. In addition, a study by Tanaka and colleagues [55] suggests that the striatum and the insula are implicated in the evaluation of reward outcomes as a function of delay. Specifically, the ventroanterior regions of these two brain structures were more activated when choices were presented in which subjects learned to select immediate rewards; conversely, the dorsoposterior regions were more activated when subjects learned to select future rewards. Tanaka and colleagues postulate that the ventroanterior parts of the insula and striatum might be involved in short-term reward prediction, whereas more dorsoposterior regions might be involved in long-term reward prediction. According to this model, the different pathways of the cortico-basal ganglia circuit might be specialized for reward prediction and action selection on different time scales [55,57]. This is indeed what we found in a recent fMRI study using a hypothetical delay-discounting task in which participants had to choose between immediate rewards and rewards with delays in the range of days to multiple years. Activity of the left-sided striatum co-varied positively with the perceived delay of the reward that will be received within one year's time versus one that will be received after one year's time. Thus, the amount of activation in this region coded for the delay of reception of the reward (See Figure I) [51].

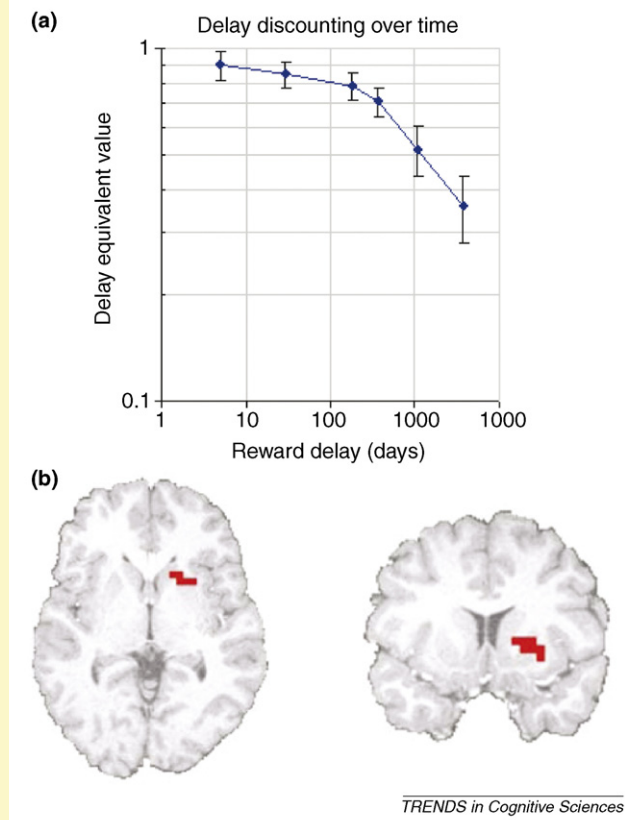

Figure I. **(a)** Two different discounting slopes plotted for delays $<$1 year and $\geq$1 year (on double-logarithmic scales). In a hypothetical delay-discounting task, subjects had to choose between a smaller reward now and a greater reward with a delay. Delays varied between 5, 30, 180 days ($<$1 year) and 365, 1095, 3650 days ($\geq$1 year). **(b)** On the axial and coronal brain slices left-sided activation of the caudate nucleus and putamen is shown for the contrast of presentations of choices between a reward now and $<$1 year and presentations of choices between a reward now and $\geq$1 year. These findings can be interpreted in the way that the activated brain regions code for the delay of reward. Adapted, with permission, from Springer-Verlag [51].

same duration during a time-production task. Cognitive models of time perception propose two mechanisms that could increase the number of pulses in an assumed accumulator [31] (see Figure 2): (i) increased attention to, as opposed to distraction from, time leads to an accumulation of more pulses over a time span, (ii) an arousal-related increased rate of pulses emitted by the pacemaker (a faster clock rate) leads to a faster accumulation of temporal units over time.

The hypothesis that impulsive choices could be due to an overestimation of time is supported by several studies showing that impulsive subjects overestimate and/or under-produce time intervals. First, when individuals were sleep deprived relative to being well rested, they were more

Box 2. Neural models of time perception

Multiple brain regions are usually activated in imaging studies on time perception suggesting that different processing components, such as attending to time, encoding an interval and keeping the representation of duration in working memory, as well as decision processes are involved [58,59]. Investigations using neuropsychological and pharmacological approaches to study time perception in animals and humans, however, have yielded the specific hypothesis that fronto-striatal circuits, which are modulated by the dopamine system, are crucial for temporal processing in the seconds range [50,60]. Individuals with structural damage to the frontal lobes [61] or traumatic brain injury predominantly affecting frontal areas [31] show impaired estimation of temporal intervals of several seconds. Neuroimaging studies with healthy volunteers show that temporal processing is predominantly associated with activation in the right prefrontal and striatal regions [50,62]. Thus, areas activated during the processing of duration are similar to those that are activated in delay-discounting tasks (see Box 1). Other brain regions, such as the cerebellum, also seem to play a decisive role in the processing of duration; however, the involvement of these regions is probably restricted to the time range of milliseconds to a few seconds [26]. Moreover, recent studies indicate that several areas of the brain can contribute to the processing of duration in the milliseconds range. Specifically, neural populations within each region could encode duration as a result of specific time-dependent neural changes, such as short-term synaptic plasticity [63]. Only future research that addresses both time perception and delay discounting in a combined study will reveal whether the same specific brain areas are involved in the processing of the two domains.

Please cite this article in press as: Wittmann, M. and Paulus, M.P., Decision making, impulsivity and time perception, Trends Cogn. Sci. (2007), doi:10.1016/j.tics.2007.10.004

impulsive, discounted delayed rewards more strongly and under-produced time intervals in the multiple-seconds range [5]. Second, impulsive borderline personality disorder patients under-produced time intervals between 10 and 90 s [32]. Third, patients with orbitofrontal cortex lesions, who were more impulsive during behavioral tests, considerably overestimated and under-produced time intervals [33]. Fourth, cocaine- or methamphetamine-dependent individuals participating in an inpatient alcohol and drug treatment program overestimated the duration of a 53 s interval, this judgment being associated with higher self-reported impulsivity [34]. Fifth, children with disruptive behavior disorders who exhibit increased impulsiveness and aggressiveness under-produced a one-minute interval more strongly than did control children [35]. Thus, findings from clinical populations clearly demonstrate that the subjective experience of time is associated with a higher level of both self-rated and behaviorally tested impulsivity.

Affective and cognitive factors altering time perception

Different mood states influence the degree to which someone attends to time or is distracted from time. Accordingly, boredom-prone individuals [36], patients with depression [37] or cancer patients with high levels of anxiety [38] perceive a slowing of the pace of time and overestimate durations in time-estimation tasks. In these cases, the acute stress might divert attentional resources away from ongoing thoughts and actions to the passage of time, which leads to an overestimation of duration [39]. In comparison, an impulsive subject who might experience distress because habitual impulsive acts often cannot be instantiated (e.g. in waiting situations) allocates more attentional resources to the passage of time, which in turn leads to an overestimation of perceived duration [34].

Alternatively, some findings support the hypothesis that impulsive individuals exhibit an increased cognitive processing speed, that is a faster pacemaker, which is consistent with increased activity level in these subjects [7]. Altered physiological conditions, for example an increase in body temperature, are associated with an overestimation of duration, an effect that has been explained by an increase in the rate of a cognitive pacemaker [40]. In animal studies, shortened production intervals have been reported after administration of stimulants, which are thought to increase the pacemaker rate [41]. Some investigators have proposed that subjects overestimate the duration of presented emotional faces relative to neutral faces because emotion leads to an increased arousal state and can alter the pacemaker rate [42].

The attention-related or activation-induced mechanisms that are proposed to alter the sense of time in impulsive individuals are not necessarily exclusive but could contribute to the phenomenon of altered time perception in an additive way [43]. For example, smokers who have cigarette cravings and feel a strong urge to smoke experienced that time passed more slowly [44]. This effect could to some extent be explained by an increased arousal due to the emotion-inducing craving symptoms. However, smokers might also attend more strongly to time as they wait for their chance to smoke.

Other experimental results are more equivocal about the relationship between impulsiveness and time estimation. For example, children and adults with ADHDs show impaired temporal processing within durations of milliseconds to multiple seconds on a variety of sensorimotor timing tasks [4,45,46]. Although these subjects showed a stronger discounting of delayed rewards, their verbal time estimates of intervals within the multiple-seconds range did not differ from estimates made by control subjects [11,43] (see also Box 3). One study even reported considerable overproductions of time intervals in children with ADHDs [47], and this finding would be consistent with the hypothesis that hyperactive children relative to comparison subjects pay less attention to the timing task. Thus, distractibility, which is a prominent feature in individuals with ADHD, might be associated

Box 3. Two essential features of studies on time perception

(1) There are basically four different methods for measuring subjects' accuracy in time estimation/perception [30]. (i) In the method of verbal estimation of duration, an interval is presented and the individual has to judge how many seconds/minutes have elapsed. (ii) In duration production tasks, a subject has to indicate when he/she thinks a certain time span has elapsed, for example by pressing a key. (iii) In duration reproduction tasks, a standard interval with a certain duration is presented. Subsequently, subjects have to reproduce the length of this interval by indicating when they believe that the duration is now identical to the standard interval. (iv) In duration comparison tasks, two intervals are presented and subjects have to decide which one is longer. In variants of this task, a subject is repeatedly exposed to a standard interval (the learning phase) and then later (the actual test phase) has to judge whether presented stimuli have equal duration compared with the standard interval.

In duration estimation and duration production tasks individuals have to translate between the experience of duration and conventional units of time (seconds, minutes). These two tasks can be used to explain individual differences in terms of attention mechanisms or the speed of a pacemaker. By contrast, the experience of time is indicated behaviorally in duration-reproduction and duration-discrimination tasks. However, because of the relative nature of the reproduction and the discrimination task (two intervals are compared with each other), any internal influence (attention, arousal) will affect the processing of both intervals – the standard and the comparison. Individual differences, that is allocation of more or less attention to time, will not reveal differences in outward performance. A disadvantage of the production as well the reproduction task is that a desire to end a trial prematurely will lead to the (re-)production of shorter intervals, a confounder especially relevant when testing impulsive individuals.

(2) It is crucial to control for the subject's ability to use counting as a strategy to keep track of time during time-estimation tasks. Chronometric counting, a language-based strategy using internal speech supports substantially more precise estimates than does the interval-timing system and is also guided by different brain structures [64]. Very often just the verbal instruction not to count is given to prevent participants from counting [5,34,48]. However, volunteers repeatedly report that the tendency to count or use other strategies for subdividing the presented time interval is rather strong. This tendency might have contributed to the lack of group differences in time estimation studies on impulsive subjects [4,65]. A reliable way to prevent participants from counting is to present them with a concurrent task during the time interval to be estimated. The concurrent task could be as simple as reading aloud numbers presented sequentially with randomized intervals, but it prevents subjects from counting internally [32,66].

Please cite this article in press as: Wittmann, M. and Paulus, M.P., Decision making, impulsivity and time perception, Trends Cogn. Sci. (2007), doi:10.1016/j.tics.2007.10.004

with slower accumulation of time pulses, which leads to longer interval productions. Finally, there was no relationship between impulsivity and time estimation in a comparably large group of young healthy college students [48]. It is possible that relatively normal variation of impulsivity levels might not be strong enough to alter the subjective experience of time. At this stage, methodological approaches and subject characteristics vary from study to study, which makes it difficult to compare some of these results directly. For future studies to overcome these shortcomings, two important factors have to be controlled for (Box 3).

Conclusions

There is a considerable body of knowledge about the cognitive-processing mechanisms that guide the experience of duration [30,49,50]. This knowledge can be brought to bear on understanding the mechanisms underlying impulsivity and self control in inter-temporal decisions [51]. Because the perception of time is strongly linked to our subjective well-being, the passage of time varies considerably depending on our emotional states. The feeling that time passes slowly seems to be a fair indicator of psychological distress resulting from an inability to focus on meaningful thoughts and to start interesting activities. Drive states, moods and emotions, visceral factors that operate in the here and now, often influence our decisions in a way so that we prefer immediate satisfaction, although in the long run we might have to face negative consequences [24]. Visceral factors might also have an impact on the sense of time, leading to a stronger focus on the present and an overestimation of time. Recently, a framework has been formulated for an anatomical and structural model for integrating interoception and the processing of emotional moments with the perception of time [52].

In summary, increased allocation of attentional resources to time and/or increased arousal states, possibly driven by emotional distress, could be the main factor that alters the way in which impulsive individuals take time into account when making decisions. According to cognitive models of time perception, the overestimation of a given temporal duration is a consequence of a stronger focus on time and of heightened arousal. We want to emphasize here that on many occasions impulsive individuals, particularly when they are distracted, do not overestimate time, which argues against a fundamental dysfunction of the ‘inner clock’. Instead, these individuals are more likely to experience a slowing down of time during situations in which they are not able to act on their impulsive urges, for example when one has to wait for a delayed reward and is confronted with the passage of time. However, more research is needed to determine the causal relationships among decision making, emotional distress and time perception (Box 4). Studies with different subject populations provide clues that the sense of time is an important factor for the understanding of altered decision making. We highlighted some methodological issues that need to be taken into account when interpreting results from time processing studies.

Understanding why individuals with clinically relevant impulsive disorders strongly neglect future consequences is the first step in developing specific interventions to alter this behavior that has negative consequences for everyday life. For example, treatment programs could use intervention strategies that manipulate the temporal delay of rewards or that cognitively restructure the perception of inter-temporal choices [17,34,53]. In addition, intervention might eventually be able to alter directly the timing system, which in turn would profoundly affect the way individuals process delayed rewards and structure behavior towards health-promoting actions.

Box 4. Questions for future research

- Is an altered sense of time in the seconds-to-minute range associated only with inter-temporal choices in a similar time range or can the association also be detected with decision tasks using longer delays?
- With respect to cognitive models of time estimation, is the subjective lengthening of duration in impulsive individuals linked to a stronger focus on time or to an increase in arousal when attending to time?
- Which temporal intervals are crucial in time perception studies? Different interval lengths will to a varying degree, depending on the subject group studied and the timing task used, be sensitive for the effects under investigation.

Acknowledgements

M.P. is supported by grants from NIDA (R01DA016663, R01DA018307) and by a VA Merit Grant. M.P. and M.W. are also funded by a grant from NIDA (1R03DA020687–01A1) and by a grant from the Kavli Institute for Brain and Mind (KIBM). The Max Kade Foundation who supported M.W. by a grant is also gratefully acknowledged. Thanks to Virginie van Wassenhove and A.D. (Bud) Craig for many helpful comments.

References

1 Ainslie, G. (1975) Specious reward – behavioral theory of impulsiveness and impulse control. *Psychol. Bull.* 82, 463–496
2 Kirby, K.N. *et al.* (1999) Heroin addicts have higher discount rates for delayed rewards than non-drug-using controls. *J. Exp. Psychol. Gen.* 128, 78–87
3 Bauer, L.O. (2001) Antisocial personality disorder and cocaine dependence: their effects on behavioral and electroencephalographic measures of time estimation. *Drug Alcohol Depend.* 63, 87–95
4 Barkley, R.A. *et al.* (2001) Executive functioning, temporal discounting, and sense of time in adolescents with attention deficit hyperactivity disorder (ADHD) and oppositional defiant disorder (ODD). *J. Abnorm. Child Psychol.* 29, 541–556
5 Reynolds, B. and Schiffbauer, R. (2004) Measuring state changes in human delay discounting: an experiential discounting task. *Behav. Processes* 67, 343–356
6 Takahashi, T. (2005) Loss of self-control in intertemporal choice may be attributable to logarithmic time-perception. *Med. Hypotheses* 65, 691–693
7 Barratt, E.S. (1983) The biological basis of impulsiveness: the significance of timing and rhythm disorders. *Pers. Individual Diff.* 4, 387–391
8 van den Broek, M.D. *et al.* (1992) Performance of impulsive and non-impulsive subjects on two temporal differentiation tasks. *Pers. Individual Diff.* 13, 169–174
9 Mischel, W. *et al.* (1989) Delay of gratification in children. *Science* 244, 933–938
10 Zimbardo, P.G. and Boyd, J.N. (1999) Putting time in perspective: a valid, reliable individual-differences metric. *J. Pers. Soc. Psychol.* 77, 1271–1288
11 Kahneman, D. and Tversky, A. (1979) Prospect theory: an analysis of decision under risk. *Econometrica* 47, 263–292
12 Kirby, K.N. and Santiesteban, M. (2003) Concave utility, transaction costs, and risk in measuring discounting of delayed rewards. *J. Exp. Psychol. Learn. Mem. Cogn.* 29, 66–79

Please cite this article in press as: Wittmann, M. and Paulus, M.P., Decision making, impulsivity and time perception, Trends Cogn. Sci. (2007), doi:10.1016/j.tics.2007.10.004

13 Laibson, D. (1997) Golden eggs and hyperbolic discounting. *Q. J. Econ.* 112, 443–477
14 Lane, S.D. *et al.* (2003) Measurement of delay discounting using trial-by-trial consequences. *Behav. Processes* 64, 287–303
15 Madden, G.J. *et al.* (2003) Delay discounting of real and hypothetical rewards. *Exp. Clin. Psychopharmacol.* 11, 139–145
16 Bechara, A. (2005) Decision making, impulse control and loss of willpower to resist drugs: a neurocognitive perspective. *Nat. Neurosci.* 8, 1458–1463
17 Critchfield, T.S. and Madden, G.J. (2006) At the crossroads of time and action: a temporal discounting primer for prospective memory researchers. In *Timing the Future: the Case for a Time-Based Prospective Memory* (Glicksohn, J. and Myslobodsky, M., eds), pp. 117–142, World Scientific Publishing
18 McDonald, J. *et al.* (2003) Effects of THC on behavioral measures of impulsivity in humans. *Neuropsychopharmacology* 28, 1356–1365
19 Carrillo-de-la-Peña, M.T. *et al.* (1993) Comparison among various methods of assessment of impulsiveness. *Percept. Mot. Skills* 77, 567–575
20 Cardinal, R.N. *et al.* (2004) Limbic corticostriatal systems and delayed reinforcement. *Ann. N. Y. Acad. Sci.* 1021, 33–50
21 Baker, F. *et al.* (2003) Delay discounting in current and never-before cigarette smokers: similarities and differences across commodity, sign, and magnitude. *J. Abnorm. Psychol.* 112, 382–392
22 Vuchinich, R.E. and Simpson, C.A. (1998) Hyperbolic temporal discounting in social drinkers and problem drinkers. *Exp. Clin. Psychopharmacol.* 6, 292–305
23 Madden, G.J. *et al.* (1999) Discounting of delayed rewards in opioid-dependent outpatients: exponential or hyperbolic discounting functions? *Exp. Clin. Psychopharmacol.* 7, 284–293
24 Loewenstein, G. (1996) Out of control: visceral influences on behavior. *Organ. Behav. Hum. Dec. Processes* 65, 272–292
25 Glicksohn, J. *et al.* (2006) Impulsivity and time estimation: casting a net to catch a fish. *Pers. Individual Diff.* 40, 261–271
26 Ivry, R.B. and Spencer, R.M. (2004) The neural representation of time. *Curr. Opin. Neurobiol.* 14, 225–232
27 Staddon, J.E.R. (2005) Interval timing: memory, not a clock. *Trends Cogn. Sci.* 9, 312–314
28 Buhusi, C.V. and Meck, W.H. (2005) What makes us tick? Functional and neural mechanisms of interval timing. *Nat. Rev. Neurosci.* 6, 755–765
29 Pöppel, E. (1997) A hierarchical model of temporal perception. *Trends Cogn. Sci.* 1, 56–61
30 Zakay, D. and Block, R.A. (1997) Temporal cognition. *Curr. Dir. Psychol. Sci.* 6, 12–16
31 Pouthas, V. and Perbal, S. (2004) Time perception does not only depend on accurate clock mechanisms but also on unimpaired attention and memory processes. *Acta Neurobiol. Exp. (Warsz.)* 64, 367–385
32 Berlin, H.A. and Rolls, E.T. (2004) Time perception, impulsivity, emotionality, and personality in self-harming borderline personality disorder patients. *J. Personal. Disord.* 18, 358–378
33 Berlin, H.A. *et al.* (2004) Impulsivity, time perception, emotion and reinforcement sensitivity in patients with orbitofrontal cortex lesions. *Brain* 127, 1108–1126
34 Wittmann, M. *et al.* (2007) Impaired time perception and motor timing in stimulant-dependent subjects. *Drug Alcohol Depend.* 90, 183–192
35 Dougherty, D.M. *et al.* (2003) Validation of the immediate and delayed memory tasks in hospitalized adolescents with disruptive behavior disorders. *Psychol. Rec.* 53, 509–533
36 Watt, J.D. (1991) Effect of boredom proneness on time perception. *Psychol. Rep.* 69, 323–327
37 Bschor, T. *et al.* (2004) Time experience and time judgment in major depression, mania and healthy subjects. A controlled study of 93 subjects. *Acta Psychiatr. Scand.* 109, 222–229
38 Wittmann, M. *et al.* (2006) The relation between the experience of time and psychological distress in patients with hematological malignancies. *Palliat. Support. Care* 4, 357–363
39 Twenge, J.M. *et al.* (2003) Social exclusion and the deconstructed state: Time perception, meaninglessness, lethargy, lack of emotion, and self-awareness. *J. Pers. Soc. Psychol.* 85, 409–423
40 Wearden, J.H. and Penton-Voak, I.S. (1995) Feeling the heat: body temperature and the rate of subjective time, revisited. *Q. J. Exp. Psychol. B* 48, 129–141
41 Meck, W.H. (1996) Neuropharmacology of timing and time perception. *Brain Res. Cogn. Brain Res.* 3, 227–242
42 Droit-Volet, S. *et al.* (2004) Perception of the duration of emotional events. *Cogn. Emotion* 18, 849–858
43 Burle, B. and Casini, L. (2001) Dissociation between activation and attention effects in time estimation: implications for internal clock models. *J. Exp. Psychol. Hum. Percept. Perform.* 27, 195–205
44 Sayette, M.A. *et al.* (2005) Effects of smoking urge on temporal cognition. *Psychol. Addict. Behav.* 19, 88–93
45 Barkley, R.A. *et al.* (2001) Time perception and reproduction in young adults with attention deficit hyperactivity disorder. *Neuropsychology* 15, 351–360
46 Smith, A. *et al.* (2002) Evidence for a pure time perception deficit in children with ADHD. *J. Child Psychol. Psychiatry* 43, 529–542
47 Cappella, B. *et al.* (1977) Time estimation by hyperactive and normal children. *Percept. Mot. Skills* 44, 787–790
48 Lennings, C.J. and Burns, A.M. (1998) Time perspective: temporal extension, time estimation, and impulsivity. *J. Psychol.* 132, 367–380
49 Brown, S.W. (1997) Attentional resources in timing: interference effects in concurrent temporal and nontemporal working memory tasks. *Percept. Psychophys.* 59, 1118–1140
50 Coull, J.T. *et al.* (2004) Functional anatomy of the attentional modulation of time estimation. *Science* 303, 1506–1508
51 Wittmann, M. *et al.* (2007) Time and decision making: differential contribution of the posterior insular cortex and the striatum during a delay discounting task. *Exp. Brain Res.* 179, 643–653
52 Craig, A.D. Interoception and emotion: a neuroanatomical perspective. In *Handbook of Emotions* (3rd edn) (Lewis, M. *et al.*, eds), Guilford Press (in press)
53 Monterosso, J. and Ainslie, G. (2007) The behavioral economics of will in recovery from addiction. *Drug Alcohol Depend.* 90, S100–S111
54 McClure, S.M. *et al.* (2004) Separate neural systems value immediate and delayed monetary rewards. *Science* 306, 503–507
55 Tanaka, S.C. *et al.* (2004) Prediction of immediate and future rewards differentially recruits cortico-basal ganglia loops. *Nat. Neurosci.* 7, 887–893
56 McClure, S.M. *et al.* (2007) Time discounting for primary rewards. *J. Neurosci.* 27, 5796–5804
57 Doya, K. (2002) Metalearning and neuromodulation. *Neural Netw.* 15, 495–506
58 Harrington, D.L. *et al.* (2004) Neural representation of interval encoding and decision making. *Brain Res. Cogn. Brain Res.* 21, 193–205
59 Rubia, K. and Smith, A. (2004) The neural correlates of cognitive time management: a review. *Acta Neurobiol. Exp.(Wars.)* 64, 329–340
60 Matell, M.S. and Meck, W.H. (2004) Cortico-striatal circuits and interval timing: coincidence detection of oscillatory processes. *Brain Res. Cogn. Brain Res.* 21, 139–170
61 Kagerer, F.A. *et al.* (2002) Cortical involvement in temporal reproduction: evidence for differential roles of the hemispheres. *Neuropsychologia* 40, 357–366
62 Hinton, S.C. and Meck, W.H. (2004) Frontal-striatal circuitry activated by human peak-interval timing in the supra-seconds range. *Brain Res. Cogn. Brain Res.* 21, 171–182
63 Mauk, M.D. and Buonomano, D.V. (2004) The neural basis of temporal processing. *Annu. Rev. Neurosci.* 27, 307–340
64 Hinton, S.C. *et al.* (2004) Neural systems supporting timing and chronometric counting: an fMRI study. *Brain Res. Cogn. Brain Res.* 21, 183–192
65 Solowij, N. *et al.* (2002) Cognitive functioning of long-term heavy cannabis users seeking treatment. *J. Am. Med. Assoc.* 287, 1123–1131
66 Rakitin, B.C. *et al.* (1998) Scalar expectancy theory and peak-interval timing in humans. *J. Exp. Psychol. Anim. Behav. Process.* 24, 15–33

Please cite this article in press as: Wittmann, M. and Paulus, M.P., Decision making, impulsivity and time perception, Trends Cogn. Sci. (2007), doi:10.1016/j.tics.2007.10.004