Weighting Waiting: Procrastination from Optimal and Suboptimal Temporal Decision Making

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Disclosures:

- I affirm that I have written the dissertation myself and have not used any sources and aids other than those indicated.
- I affirm that I have not included data generated in one of my laboratory rotations and already presented in the respective laboratory report

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ABSTRACT

Procrastination is a universal phenomenon, with a significant proportion of the population reporting interference and even harm from such delays. Why do people put off tasks despite what are apparently their best intentions, and why do they deliberately defer in the face of prospective failure? In this thesis, we elucidate plausible mechanisms behind such choices in a sequential decision-making framework using Markov Decision Processes (MDPs) and Partially Observable MDPs (POMDPs). We model procrastination as a choice in time of delaying the start, continuation or completion of a task at hand. We introduce a taxonomy of different types of procrastination and potential sources for each of these types. We simulate the operation of some of these mechanisms: including previous suggestions such as an effect of temporal discounting and inconsistencies that stem from differential discount factors for rewards and effort; and novel possibilities that do not depend on discounting, including the resolution of uncertainty, anticipation of better conditions and expected or unexpected changes in circumstances. The simulations illustrate a number of scenarios, and systematically delineate the influence of the multiple components of task structure. We also suggest experiments that can test these types and potential interventions.

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1 INTRODUCTION

Procrastination is prevalent. Many of us have worked hastily on an assignment in the last minute, sat on tax returns for weeks, repeatedly put off going to the gym, etc. Procrastination is also experienced at social and national levels, for example, delaying action on pressing problems like climate change. The phenomenon is widespread with 80% of students and 20% of adults affected (Steel, 2007). In fact, many lose money (O'Donoghue and Rabin, 2001), suffer effects on health (Sirois, 2007), and waste precious time due to delays. Most procrastinators want to reduce it (O'Brien, 2002). But, what causes procrastination? How can it be assuaged? There is still much to know and understand.

In the first section, we first describe some of the main themes discussed in the literature. Then, in section 2, we offer a taxonomy of procrastination types and mechanisms based on decision structure and causes for delay.

1.1 WHAT IS PROCRASTINATION?

The first challenge in the scientific study of procrastination lies in defining it. In the broadest sense, it is the decision to delay, to do something later and not now. The crucial intuition is that not all delays can be considered as procrastination, as any efficient plan (and its subsequent execution) requires prioritising tasks in time and putting off some in favour of others. That is, one cannot do everything all at once. This calls for qualifying the delays to be considered procrastination. We now summarise some attempts at delineating what type of delays constitute procrastination and identify some problems with them.

A popular definition from (Steel, 2007) and colleagues characterises procrastination as 'a voluntary delay of an intended course of action despite expecting to be worse off for the delay'. This definition includes two components: deviating from an intended plan of action and sub-optimality. However, even without such a deviation, the intended time to act can itself be planned too late to meet a deadline. In practice, such delays are also considered procrastination (Fernie et al., 2017; Le Bouc and Pessiglione, 2022). In fact, (Fernie et al., 2017) distinguish between passive or unintentional procrastinators who delay a task despite good intentions vs active or intentional procrastinators who delay a task on purpose (perhaps, in an attempt to maximise performance). With respect to sub-optimality, delays that are too long can still be optimal from the point of view of procrastinators, who might be maximising their own internal utility functions.

Others draw a distinction between task avoidance (abandoning a task altogether) and task delay, regarding only the latter as procrastination. A corollary is that any explanation of procrastination should also be able to account for why people eventually get around to doing a task after initial reluctance (Zhang et al., 2019). It does make sense to draw a distinction between a decision to delay a task and a decision to not engage in a task in the first place. However, it must be noted that repeated procrastination can lead to a failure to complete. In fact real world examples do include such cases: students not completing all assignments with some missing the deadline (Steel et al., 2018) or delaying the redemption of vouchers to the point of foregoing them (Shu and Gneezy, 2010). Others draw a distinction between indecision and delaying a decided action, but decisions can also be actions that are delayed. In fact, some scales like the Melbourne Decision Making Questionnaire (DMQ) involve a few questions about procrastinating decisions (Mann et al., 1997) (like 'I delay making decisions until it is too late' or 'I waste a lot of time before getting to the final decision'). These are some main distinctions that previous studies have made.

In Chapter 2, we attempt to fix some of the problems of these various definitions and integrate them into a classification of procrastination types.

1.2 MEASURES OF PROCRASTINATION

How are these conceptions of procrastination operationalised in real-world studies and what tools are used to measure them?

The most common way to measure procrastination is the use of self-reported scales and questionnaires. Some popular scales include the General Procrastination Scale (GPS) (Lay, 1986), Adult Inventory of Procrastination (AIP) (McCown et al., 1989), Decisional Procrastination Scale (DPS) (Mann et al., 1997), Irrational Procrastination Scale (IPS) (**?**), Pure Procrastination Scale (PPS) (Steel, 2010), etc. The items on these traditional scales capture:

1. delays beyond what is intended (eg: I find myself performing tasks I had intended to do days before; I am continuously saying "I'll do it tomorrow")
2. difficulty in meeting deadlines (eg: I don't get things done in time; I find myself running out of time)
3. doing things in the last minute (eg: I buy even essential things in the last minute; I do not do assignments until the day before a deadline)
4. wasting time (eg: in preparation for a deadline, I often waste time by doing other things

or trivial matters; when I should be doing one thing I do another; I could have spent my time better)

5. unnecessary or unreasonable delays (eg: I generally delay before starting on work; I delay tasks beyond what is reasonable)

6. disadvantage due to the delay (eg: missing deadlines; efficiency or well-being suffers; my life would be better if I did some things earlier)

A factor analysis of three of the procrastination scales (GPS, AIP, DPs) yielded three factors: the first captures habitual and disadvantageous delays, the next is associated with rushing and missing appointments, and the final captures a lack of promptness (Steel, 2010).

In contrast to this irrational form of procrastination accompanied by negative outcomes and emotions, the Active Procrastination Scale (APS) was developed to capture purposeful delays made in order to improve performance or use the efficiency gained from time pressure (Choi and Moran, 2009). Critically, no evidence was found that such preferences had any association with better achievement or performance (Pinxten et al., 2019). This shows that intentional delays are indeed real but effects of active procrastination have to be better characterised. (Fernie et al., 2017) developed the Unintentional Procrastination Scale (UPS) to better identify specifically unintentional types, separate from voluntary delays.

There are also task-based (and task-specific) measures of procrastination behavior which simply calculate the extent, rate or pattern of delays. (Lieder et al., 2019) measured it as the completion rate in a naturalistic task consisting of writing assignments, (Steel et al., 2018) measured the cumulative sum of number of assignments submitted through the course of an undergrad psychology class in conjunction with course grade and other performance measures, (Shu and Gneezy, 2010) also measured a completion rate of voucher redemptions and museum visits in their survey populations and more recently, Zhang and Ma (2023) calculated the mean completion time of compulsory research units in a psychology course. In more controlled tasks like in (Le Bouc and Pessiglione, 2022) and (Zentall et al., 2020), procrastination is measured as percentage of choices to delay an action than doing it earlier.

1.3 CAUSES OF PROCRASTINATION

Equipped with an understanding of procrastination as a construct and tools to measure it, past studies have identified some correlates and factors that are very useful in illuminating the possible causes of procrastination.

One line of empirical work has focused on discerning personality traits and other such individual differences that are correlated with procrastination behavior which also has trait-like stability across time and contexts (**?**). The big-five framework of personality traits has been particularly popular in these attempts to find predictive factors (Digman, 2003). Conscientiousness is a factor that includes qualities of responsibility, self-regulation and self-control, organisation, discipline, achievement motivation and industriousness (Costa et al., 1991). Procrastination can be understood partly as a lack of self-control, organisation and other aspects of conscientiousness. Indeed, negative correlations between procrastination and these sub-factors of conscientiousness have been found in various populations (Lee et al., 2006). Subsequent meta-analyses have shown an average correlation of -0.62 (Steel, 2007). Some characteristics of another big-five personality trait, neuroticism like impulsiveness, low self-esteem, worrying, irrational beliefs about oneself, perfectionism and self-handicapping have also been proposed as reasons for procrastination (Ellis and Knaus, 1977; Lay et al., 1992; Pychyl and Flett, 2012). Self-efficacy and self-handicapping show high average correlation (-0.38 and 0.46) (Steel, 2007). Among other sub-factors of neuroticism, however, only impulsiveness and some irrational beliefs shows a strong average correlation (Steel, 2007). In fact, effects of neuroticism disappear when conscientiousness is accounted for (Lee et al., 2006). On the other hand, factor analyses of questionnaires have revealed some dimensions that include specific forms of irrational beliefs like fear of failure as reasons for procrastination (Solomon and Rothblum, 1984). Effects of other factors like openness/ intelligence, extraversion and agreeableness do not have a significant association with procrastination (Steel, 2007). Procrastination was also linked with maladaptive coping styles to stress, like denial, self-blame and substance-abuse (Sirois and Kitner, 2015) and prioritisation of short-term mood regulation over long-term goals (Sirois and Pychyl, 2013).

Another approach has been to identify characteristics of tasks that are most likely to be procrastinated. Tasks that are aversive in some way, like being too effortful, anxiety-inducing or boring are one of the most common reasons why people postpone tasks (Ferrari and Scher, 2000; Kachgal et al., 2001). Task aversion consistently turns up as a dimension in factor analyses of procrastination questionnaires (Steel, 2007). The timings of rewards and punishments, deadlines and time pressure in a task is also indicated to play a role. For example, students indicate that they would delay less as a task nears a deadline (Schouwenburg and Groenewoud, 2001).

1.4 AIM OF THE PROJECT

This brief review of research in procrastination reveals the following. The numerous, complementary definitions of the construct encapsulate everything from unintentional to intentional delays, optimality, defections, necessity and advantage. This suggests that there are multiple dimensions of interest that distinguish different types of procrastination. These are also queried in the various questionnaires. Next, there are also as many explanations and reasons for why someone procrastinates as suggested by the correlations.

Our aim is to tackle the multifaceted nature of this phenomenon by constructing a taxonomy based on principles from decision theory and reinforcement learning. We integrate the many complementary understandings and routes to procrastination into the framework. This is followed by simulations of some of the explanations that elucidate details of how task characteristics and decision structure interact with these plausible mechanisms of temporal preference for delays.

2 TAXONOMY

2.1 TAXONOMY AND DEFINITION

Based on the limitations of previous definitions and the notions captured by questionnaires, we propose the following main types of procrastination:

1. Deliberately delaying a task due to rational or irrational reasons, leaving insufficient time to complete it satisfactorily, losing time or forgetting.

2. Delaying to a later time in spite of intending to do earlier.

3. Not committing to a time of action and hence missing a deadline, forgetting or losing time in the process.

4. Abandoning a task at first and then deciding to do it later on.

Here, being rational means acting to maximise one's personal utility function. What do the delays specified by the aforementioned types actually look like? The first type refers to the delays where a person sticks to an intended time of action but finds it insufficient for a deadline. These could look like decisions to delay as a means to optimise performance or miscalculations in the attempt to do so. The second type captures the more conventional conceptions of reneging (perhaps repeatedly) on an intended time point of action. The third type includes delays from wasting time or simply not deciding on a time to work despite knowing the task should be done and the final one covers effective delays stemming from the decision to work after initially choosing to abandon the task. These choices can be visualised as a decision tree as shown in Figure 2.1. The structures of the four types of delays are shown as schematic diagrams accompanying their respective branch of the tree.

As we shall see in Chapter 3, the delays can be in the start, continuation or completion of a task. So for example, a job may be started promptly, but the subsequent work might be procrastinated.

2.2 IN WHAT SITUATIONS DO PEOPLE PROCRASTINATE?

As already hinted at in the previous section, the reasons for and type of procrastination observed is very much dependent on the type of situation and task encountered. We consider and categorise both the structure of tasks and the task attributes or characteristics that affect procrastination.

2.2.1 Task structure

Presence of deadlines and time-pressure: Procrastination is often observed in situations where a task must be completed by a deadline, where people put the task off even at the prospect of not making it in time. A popular example is the time-bound submission of assignments by students. Students often delay submissions until close to the deadline (following a hyperbolic curve), sometimes even missing the deadline (Lieder et al., 2019; Steel et al., 2018). However, dilatory behavior can also be observed in more relaxed time conditions with far-away (or no) deadlines or situations where there is no time pressure as such. For example, pigeons and people delay effortful actions in laboratory tasks where a forced choice is presented between exerting effort at two points in time (Le Bouc and Pessiglione, 2022; Zentall et al., 2020). Here, subjects are not under any time pressure but simply have to indicate their preferred time of action. Other examples with no deadlines include scheduling medical appointments or starting a workout routine or fitness program.

Delays in rewards: Procrastination often arises in tasks where the benefits are temporally distant from the time of action. This includes submission of assignments where the grades come at a lag (Steel et al., 2018), signing up for an employer's health plan (Previtero, 2008), visiting a dentist or doctor where many a time the benefit is only the prevention of future harm or saving up for retirement where the fruits of prudence can only be enjoyed several years or even decades later (Rozental and Carlbring, 2014). However, procrastination can also occur in tasks where rewards are experienced immediately. People seem to put off redeeming gift vouchers at the risk of expiry, even if benefits are almost instant (Shu and Gneezy, 2010), subjects prefer to delay actions in controlled experiments where quantified rewards can be obtained immediately for certain efforts (Le Bouc and Pessiglione, 2022).

Changes in circumstance: Task characteristics like utilities obtained from a task or efforts required to complete it, need not stay constant in time, but can be evolving. This might contribute to procrastination in the form of changes in initial plans or non-committing in anticipation of appropriate circumstances.

2.2.2 Task characteristics

Aversive and enjoyable tasks: People consistently indicate that tasks they find unpleasant, frustrating, boring, effortful, or anxiety-inducing (Steel, 2007) are top reasons for procrastination. Further, the more one dislikes a task, the more likely it is to be delayed (Zhang et al., 2019).

Therefore, aversiveness might contribute to delays. On the other hand, tasks which people consider enjoyable or not particularly aversive like redeeming a gift voucher or visiting museums are put off too (Shu and Gneezy, 2010), though these tasks also involve some effort (like filling a form or expending time to enjoy the museum). In addition, tasks often come with an outcome utility (Zhang et al., 2019). This can be a negative outcome on failure to complete the task (like bad grades or decaying teeth) or a positive outcome on completion (like a redeemed gift).

Uncertainty in outcomes: One aspect that has been relatively unconsidered in past analysis is the uncertainty regarding different aspects of the tasks. In some tasks, the outcome from performing the task is certain, like the value of a gift voucher or the reward size from executing an action in a controlled task. In others, the outcome is uncertain, like the grade for an assignment, health outcome in the future, etc. There can be uncertainty in the efforts required to obtain (or avoid) outcomes, uncertainty regarding current state be it health status or amount of knowledge accumulated at present (for a test).

2.3 EXPLANATIONS

Now that we have laid out the types of procrastination and situations in which they occur, we turn to examining explanations for how they emerge. Firstly, what persuades someone to engage in a task at all and not abandon it? Do they commit to a time of action or not? If they don't, what makes them do the job later? Why would someone commit to doing it too late? What are the mechanisms that drive defections on these plans? These can be envisioned as reasons for relevant branch-points of the tree shown in Figure 2.1. For each of these questions, some are suggestions from previous research, while others are mechanisms we propose.

2.3.1 Why engage?

The first question that arises is why it is worth engaging in a task and not abandon it all together. That is, why plan to work even if later? One motivator can be the potential reward (a good grade, better health, internal satisfaction) to be gained on completing the task successfully or to avoid an additional negative outcome on non-completion (bad grade, losing money, internal costs like feeling of failure). It could then make sense to forsake the task if the efforts required, be they physical or cognitive energy, money or time required outweigh the potential outcomes from completion. In the next sections, we discuss what might underlie a decision to delay a job that's worth engaging in.

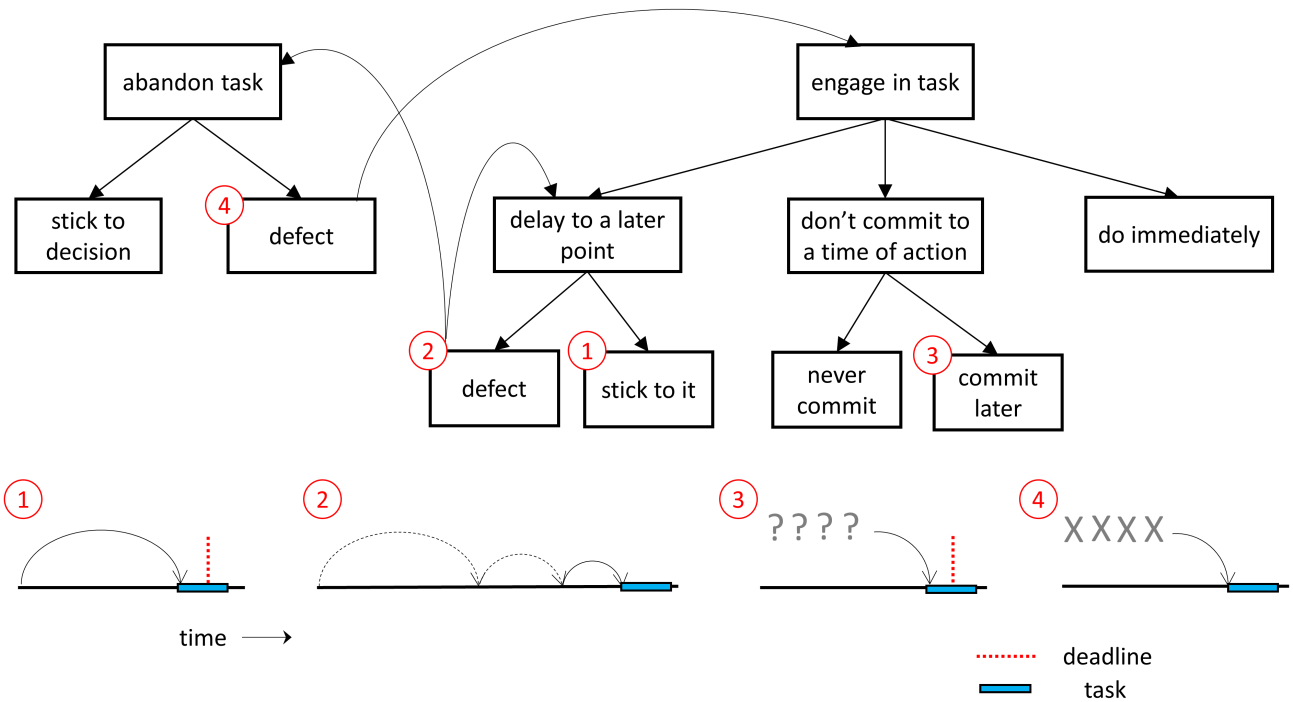

Figure 2.1. An illustration of the type of delays in the form of a tree that constitutes procrastination. Possible explanations for each branch point can aid our understanding of why someone procrastinates.

2.3.2 Why commit but late?

Temporal discounting

A dominant explanation provided for procrastination is related to temporal discounting of outcomes. It refers to the subjective diminishment of reward with delay. (Steel and König, 2006) proposed the temporal motivation theory (TMT) of procrastination where the utility of a task scales with the expected value from the task and is inversely proportional to the delay to the reward with a discounting factor (γ) capturing sensitivity to delay. According to this theory, procrastinators are impulsive and hence prefer tasks with immediate rewards (can be thought of as temptations) to more temporally distant ones. Hence, working on a task with distant rewards (like an assignment that is graded after the deadline) is procrastinated in favor of immediate temptations, risking missing the deadline. Recently, (Zhang and Ma, 2023) demonstrated correlation between procrastinators in a real-world task and their respective discount factors found empirically.

(Zhang et al., 2019) generalised this framework by also including the intrinsic costs of engagement, usually negative, especially for aversive tasks. Here, procrastination is a result of opposing motivations to postpone costs of engagement in the short term and an increasing motivation (towards the delayed reward) to obtain the positive outcome. Hence, delaying can occur even if there isn't a competing task. Procrastination happens through a series of decisions of to do a task now or not until the net utility is higher for doing. The TMT relies on the presence of a delay between doing the task and delivery of the outcomes. The motivation to engage in a task increases as the delay to receiving the reward (usually at the deadline) reduces. But, as mentioned before, tasks where the rewarding outcome is delivered immediately are also procrastinated. Further, while being a dominant explanation, procrastination behavior is not synonymous with impulsivity. Hence, we also outline other explanations that do not specifically depend on discounting.

Self efficacy

Self-efficacy can be thought of as the estimated probability to achieve an outcome on doing an action. Low self-efficacy has been associated with procrastinating behavior through responses on questions testing such beliefs (Rozental and Carlbring, 2014). A simple explanation can build on the TMT, where people with low self-efficacy have a low expectancy to obtain a reward and so, it is not worth engaging in a task until relatively later to obtain a delayed reward. Such beliefs in inability can become self-fulfilling, with lower performance reinforcing belief in low efficacy which in turn can lead to procrastination and lower performance on task (Rozental and Carlbring, 2014).

This reasoning can also seem a bit simplistic. Someone who is aware of their low efficacy might decide to actually start earlier to ensure better chances of finishing the task in time. We might find the opposite problem where, over-estimation of one's abilities or belief that a task is easier than it is, might result in a decision to start later than required. This is a gap between a person's estimates and the real ability or task difficulty. A specific case of such a bias could be the planning fallacy which involves an underestimation of the amount of time it will take to complete a task (Rozental and Carlbring, 2014).

Arousal

Procrastination might result from a belief that there is a more opportune time in the future to complete the task successfully or more efficiently. For example, performing a task closer to a deadline could improve efficiency or general arousal due to the urgency induced by the time pressure Steel (2007). We suggest that people might then decide to start a task later in time to utilise the improved performance, finding themselves unable to engage due to insufficient motivation in the present. Perhaps, they do not foresee that it could leave inadequate time to complete the task. However, one could eventually learn to find the 'right time' to start a task from errors on repeated encounters with the situation. In past studies, task deadline and delay for a reward have generally been identical, potentially conflating their separate effects.

Ego protection

Someone anticipating failure or under-performance at a task could plan to delay it long enough or engage in unrelated tasks in an act of self-handicapping, setting themselves up for failure Ferrari (1992); Rozental and Carlbring (2014). This allows them to deflect blame to the act of starting late rather than their inability, preserving their own reputation in the process.

Heuristics

Another perspective on the impulsivity explanation comes from (Lieder et al., 2019). They posit that planning out the optimal set of actions in the future (optimal policy) is not always possible due to limited cognitive resources and even if planned, a lapse in self-control might override this long-term plan in favour of immediate impulses. This could be described as a heuristic where only short term rewards are optimised over tasks with more distant rewards like a writing assignment with a deadline, leading to a delay similar to the discounting explanation in the temporal motivation theory.

In addition, we propose the three following novel explanations for this type of delays:

Anticipation of a better future

Belief (correct or incorrect) that the situation will improve in the future can lead to a decision to postpone. While this could still be the optimal decision in terms of utility, this might lead to subpar performance on the task.

Avoiding information

People could be worried that a task will turn out to be more difficult than they thought (for example, in terms of effort required or their own skill level). Hence, they could delay starting a task to avoid finding information that would confirm their fears. The benefit of doubt is the possibility that a positive outcome can be gained while resolving uncertainty eliminates this. In short, people might delay resolving uncertainty due to a pessimistic expectation.

Negative discounting

Negative discounting is the preference to have positive outcomes later and negative outcomes sooner. It accounts for more far-sighted behaviour as opposed to the traditional discounting theories discussed before which explain myopic behaviour. (Loewenstein, 1987) posits an anticipatory value associated with the time preceding an enjoyable or aversive outcome that could lead to negative discounts. So pleasurable events like a kiss from a favourite celebrity might be delayed in time in anticipation (savouring), but not forever due to a positive discounting of value. Similarly, anticipation of negative events like a shock can induce a dread that causes one to want to expedite the outcome instead of avoiding it indefinitely. Hence, for immediate rewards, procrastination can arise directly from delays due to savoring.

2.3.3 Why not commit?

Waiting for an opportune time

Unfavourable circumstances or environment in the present can lead to a decision to put off doing a task now and wait for more suitable circumstances where performance would be better. This might manifest in a non-commitment to act until better conditions are in sight. A potential danger with this is that the better future might never arrive or arrive too late (for a deadline) or the circumstances might actually get worse with time without action.

Waiting for information

When some aspects of the task are uncertain to people, it might make sense to collect more information before working, especially when a decision is irreversible. Some examples could be waiting to see if a medical problem can be mitigated without an expensive intervention, or delaying submitting a paper in the hope that it could be made better. This could lead to repetitive delaying until 'enough' information has been acquired. There are also often different preferences regarding how much information to collect before committing to a decision with some being more averse to risk while others being more tolerant (Choi et al., 2007). For decisions about when to do a task, some might decide to wait for longer to learn or collect more information in order to perform better.

Rumination

The previous two explanations are new explanations proposed by us. Another related mechanism suggested before for this type of delays could be rumination or worry, both of which have been linked to procrastination (Constantin et al., 2018). Rumination is repetitive negative thought about past events, while worry is also repetitive thought but about the future perhaps due to (and in an attempt to resolve) uncertainty in future outcomes. These can be conceived as an internal evidence accumulation process Bedder et al. (2023); Watkins and Roberts (2020). Both can lead to dilatory behavior through waiting to collect enough information before working, like in the previous case.

2.3.4 Why defect?

Non-exponential discounting

In the section on temporal discounting, we discussed one aspect of the discounting curves that may underlie procrastination. Namely, the subjective reduction in value with delay. Another important aspect is the shape of the curve itself. It turns out that only exponential discount curves preserve a consistent preference between different options in time. All non-exponential curves lead to preference reversal, where a choice between distant outcomes can reverse closer to the events contrary to initial intentions (Ainslie and Haslam, 1992). For our purposes, this means that a decision to work on a task in the future can be defected on closer to the time of working, hence, procrastinating yet again.

Differential discount factors

Another explanation is that procrastination could arise from steeper discounting of effort costs associated with a task than rewards, making a task look more effortful now than later, but not much more rewarding. (Le Bouc and Pessiglione, 2022) model delays as one-off or repeated decisions about when to do an effortful task (in return for immediate reward) based on a maximisation of net discounted utility from efforts and rewards. From laboratory and at-home experiments, they find a steeper discounting of efforts than rewards associated with procrastination behavior.

Having different discount factors also has implications for the time consistency of the temporal decisions, even if each is exponential. The best time to start working can shift in time, leading to a defection on previously intended point of action. We discuss this case extensively in Chapter 3.

This, of course, doesn't explain *why* such differential discounts exist in the first place. One suggestion comes from (Shu and Gneezy, 2010) who also put forth this theory in an attempt to account for the findings that people put off going to exhibitions and museums or redeeming gift vouchers, both of which have immediate pay-offs. For (Shu and Gneezy, 2010), the underestimation of future efforts could be due to an over-prediction of free time one will have in the future compared to now, perhaps inflating the perceived opportunity costs of engaging in the task now (Zauberman and Lynch, 2005). Another related idea is that people pay more attention to whether a task is feasible in the present but more on desirability of the reward it brings in the future (Trope and Liberman, 2003).

(Shu and Gneezy, 2010) find that introducing shorter deadlines actually improves rate of redemption / completion of tasks. Similarly, (Le Bouc and Pessiglione, 2022) find an expedition of time of effort exertion when delays are framed as precise dates to act rather than deadlines. These are not explained by the theories of differential effort perception, suggesting the role of other components like dread (Loewenstein, 1987) or arousal closer to the deadline (Steel, 2007).

Unexpected changes in task or environment

In addition to these discounting-based mechanisms suggested by previous literature, we propose another explanation for defections. Unexpected changes in the task or some aspect of the environment can cause someone to defect on their initial plans. This can mean going back on the intention to act when the anticipated suitable conditions do not arrive or deciding to work due to unexpected improvements despite initially deciding to abandon the task.

2.3.5 Learning theories

Learning theories describe how decisions to delay might be reinforced to start even later the next encounter with the same or similar task, ultimately leaving insufficient time for the task. However, there can also be learning away from procrastination with repeated encounters with negative consequences of delaying a task. In fact, there is evidence that people procrastinate less with practice, and in general, with age Baumeister et al. (1994); Steel (2007).

Delay reduction theory

The delay reduction theory is a learning theory according to which, the closer a stimulus occurs in time to a primary reinforcer, the more effective it is as a conditioned reinforcer (Fantino et al., 1993). (Zentall et al., 2020) use this to explain a series of findings of procrastinating behavior in pigeons, where the birds prefer to delay an aversive gap or an effortful pecking requirement preceding reinforcement. In fact, even in the absence of an aversive event, pigeons prefer a long followed by a short, signalled interval to reinforcement rather than a short-long chain (Zentall et al., 2018). The authors think of this as a route to procrastination, where an action or a response made closer to a primary reinforcement is reinforced, hence prompting learning to delay actions. The assumption here is, of course, that the primary reward occurs at a fixed time in the future. (Zentall et al., 2020) actually observe that the aversive gap significantly increases preference for the delayed option compared to their original experiment in (Zentall et al., 2018).

Relief

Performing an aversive task can induce a negative utility of anticipation with time to the outcome (dread) Loewenstein (1987). However, eventual completion of such a task can lead to an (unexpected) positive relief in proportion to the dread, which might reinforce performing an action even later in time with repeated presentations of the task.

3 RESULTS

We now simulate the operation of some of the mechanisms that we described verbally in Chapter 2. This serves to put detail in the theory, illustrating the workings of the mechanisms and highlighting essential components that lead to delays and the effects of the various parameters.

3.1 METHODS

3.1.1 Markov decision processes

We use Markov decision processes (MDPs) to model mechanisms of procrastination in several task structures. MDPs provide a mathematical framework to model sequential decisions where a choice now can affect rewards collected and possible actions in the future (**?**). MDPs formalise task characteristics like reward schedules and task dynamics. Further, optimal choices can easily be derived using dynamic programming methods to maximise expected sum of future rewards. In general, an MDP is a 4-tuple (S, A, P, R), consisting of:

1. set of states of the environment an agent occupies at a given timestep ($s_t \in S$),
2. set of actions from which a choice is made at every timestep ($a_t \in A$),
3. transition probabilities $P(s, a, s')$ of going to a state s' on taking an action a in state s. This specifies the dynamics of the task,
4. reward function $R(s, a, s')$ that defines reward obtained on taking action a in state s and transitioning to state s'.

The conventional goal is to find a policy $\pi(s, a)$ that specifies which action to perform in a state to maximise the discounted or un-discounted expected sum of rewards (returns) over a finite (task ends at $t = T$) or infinite horizon: $\mathbb{E}\left[\sum_{t=0}^{T} \gamma^t R(s, a, s')\right]$ or $\mathbb{E}\left[\sum_{t=0}^{\infty} \gamma^t R(s, a, s')\right]$. The discount factor, $0 \leq \gamma \leq 1$ devalues future rewards with time compared to present ones at a constant rate. So, agents with γ close to 0 are myopic and value immediate rewards much more than future rewards while agents with γ close to 1 are more far-sighted. The discount factor also guarantees convergence of the reward while optimising in the infinite horizon case. In the next sub-section, we will consider a case with not one common discount factor but different ones for rewards and costs.

In practice, this optimisation problem can be solved recursively using dynamic programming methods. This is because the returns can be maximised by choosing the action that maximises the sum of the immediate reward on taking the action and the subsequent expected returns from the future state, which can be written yet again as a similar sum:

$$V^*(s) = \max_a \Big\{ \sum_{s'} P(s,a,s') \left(R(s,a,s') + \gamma V^*(s') \right) \Big\} \tag{3.1}$$

3.1.2 Solving MDPs with different discount factors

In Section 3.3, we consider a case where there is not one but two separate discount factors for rewards and costs (γ_r, γ_c). This changes the objective function that is to be maximised:

$$\mathbb{E}\Big[\sum_{t=0}^{T} \gamma_r^t\, R(s,a,s') + \gamma_c^t\, C(s,a,s') \Big]$$

where, $R(s,a,s')$ represent only the positive immediate rewards, and $C(s,a,s')$ exclusively represent the negative immediate rewards (costs). This eliminates the recursive structure that we described previously because the discount factors can no longer be factored out at every expansion of the sum.

However, the problem can still be solved in the finite horizon without having to do a brute force search through all possible policies to find the maximising one. Here, we derive the equations to find the policy that maximises the expected returns. Consider the case with a finite horizon with T timesteps. At an arbitrary timestep $t = k$, the returns for the rest of the horizon is given by:

$$V^*_{(k,k)}(s_k) = \max_{\pi_{k,k}} \mathbb{E}\Big[\sum_{t=k}^{T} \gamma_r^{t-k}\, R_t + \gamma_c^{t-k}\, C_t \Big] \tag{3.2}$$

$$= \max_{a_k} \sum_{s_{k+1}} P(s_k, a_k, s_{k+1}) \big(R_k + C_k + \max_{\pi_{k,k+1}} \mathbb{E}\Big[\sum_{t=k+1}^{T} \gamma_r^{t-k}\, R_t + \gamma_c^{t-k}\, C_t \Big] \big) \tag{3.3}$$

$$= \max_{a_k} \sum_{s_{k+1}} P(s_k, a_k, s_{k+1}) \big(R_k + C_k + V^*_{(k,k+1)}(s_{k+1}) \big) \tag{3.4}$$

where in general for $l \geq k$,

$$V^*_{(k,l)}(s_l) = \max_{a_l} \sum_{s_l} P(s_l, a_l, s_{l+1}) \big(\gamma_r^{l-k-1}\, R_l + \gamma_c^{l-k-1}\, C_l + V^*_{(k,l+1)}(s_{l+1}) \big) \tag{3.5}$$

Notice that $V^*_{(k,k+1)}(s_{k+1}) \neq V^*_{(k+1,k+1)}(s_{k+1})$, the returns for the rest of the horizon when starting at timestep $k+1$.

$V^*_{(k+1,k+1)}(s_{k+1})$ would actually be $= \max\limits_{\pi} \mathbb{E}\left[\sum\limits_{t=k+1}^{N} \gamma_r^{t-k-1} R_t + \gamma_c^{t-k-1} C_t\right]$, while

$V^*_{(k,k+1)}(s_{k+1}) = \max\limits_{\pi} \mathbb{E}\left[\sum\limits_{t=k+1}^{N} \gamma_r^{t-k} R_t + \gamma_c^{t-k} C_t\right]$ from equations 3.3 and 3.4.

Hence, the best sequence of actions to take from $t = k$ cannot simply be found by calculating the action that maximises the sum of immediate rewards and expected future returns, and appending the best action sequence from the future state. Instead, a separate policy has to be computed starting at each timestep. The resulting policy can therefore be potentially time-inconsistent. We will return to the implications of this inconsistency in Section3.3.

3.1.3 Partially observable Markov decision processes

Partially observable Markov decision processes (POMDPs) are a generalisation of the MDP where the states are not completely observable - i.e., there is an uncertainty associated with which state the agent occupies (Kaelbling et al., 1998). We employ a POMDP to model the case in Section 3.6. In addition to the components of set of states S, set of actions A, transition probabilities $P(s'|a, s')$ and reward function $R(s, a)$ in a typical MDP, POMDPs are also associated with:

1. set of observations Ω,
2. probability $P(o \mid s', a)$ of observing o on transitioning to s' on taking action a.

The noisy observations provide imperfect information about the underlying environment state which can then be used to infer the probable world states and plan the optimal actions by optimising the expected sum of rewards, $\mathbb{E}\left[\sum\limits_{t=0}^{\infty} \gamma^t R_t(s, a)\right]$, like before.

The agent can maintain a posterior probability of the underlying states given the observations and actions taken, called the belief state $b(s)$. Since the hidden states are Markovian, the belief state is also Markovian, requiring only the previous belief state, action taken and current observation to calculate. The belief can be updated simply using Bayes rule:

$$b'(s') = P(s' \mid o, a, b) \tag{3.6}$$

$$= \frac{P(o \mid s', a) \sum_s P(s' \mid s, a)\, b(s)}{P(o \mid b, a)} \tag{3.7}$$

where

$$P(o \mid b, a) = \sum_{s'} P(o \mid s', a) \sum_{s} P(s' \mid s, a)\, b(s) \tag{3.8}$$

Belief MDP Given this Markovian property of the posterior beliefs, the POMDP can itself be converted into an MDP with the observable beliefs as continuous states – the belief-MDP. The belief update equation 3.6 constrains the possible beliefs b' that can be reached from the current belief b, which depends on the action a taken and the subsequent observation o. The transition function over the belief states ($\tau(b, a, b')$), i.e., the probability of going to belief b' on taking action a in belief state b is given by marginalising over the observations:

$$\tau(b, a, b') = \sum_o P(b' \,|\, b, a, o)\, P(o \,|\, b, a) \tag{3.9}$$

where

$$P(b' \,|\, b, a, o) = \begin{cases} 1, & \text{if } b' \text{ is the belief update from } b, a, o \\ 0, & \text{otherwise} \end{cases}$$

and $P(o \,|\, b, a)$ is given by equation 3.8. The reward function of the belief-MDP is the expected reward of the POMDP:

$$r(b, a) = \sum_s b(s) R(s, a)$$

Finally, the optimal policy can be found by maximising the value function over the belief states:

$$V^*(b) = \max_a \left\{ r(b, a) + \gamma \int_{b'} \tau(b, a, b') V^*(b') \right\} \tag{3.10}$$

$$= \max_a \left\{ r(b, a) + \gamma \sum_o P(o \,|\, b, a) V^*(b') \right\} \tag{3.11}$$

We solve the belief-MDP numerically by discretising the continuous belief space into a grid with spacing of probability $= 0.05$. We use bilinear interpolation to get the values for beliefs that are not on the grid and barycentric interpolation for values on the edge of the belief space simplex. We perform regular value iteration on this discrete belief space and halt when the maximum difference between subsequent value functions is less than $\epsilon = 0.001$. Note that, for a POMDP with n hidden states, the belief space is $(n - 1)$-dimensional because the belief on the n^{th} state is constrained by the belief on the other $(n - 1)$ states (the probabilities have to add up to 1).

3.2 TEMPORAL DISCOUNTING

3.2.1 Set-up

The first case that we explore is the often-considered case of temporal discounting. To illustrate the mechanism, we simulate a simple, deadlined assignment submission task that consists of three states of completion: a start state ($s_t = 0$), an intermediate state ($s_t = 1$) where the task is half-completed and a final state ($s_t = 2$) where the task is finished. At every timestep, the agent can choose between the actions of 'work' ($a_t = W$) and 'shirk' ($a_t = S$). On working, the agent transitions to the next state with probability η (also called efficacy) or remains in the same state with probability $1 - \eta$. Working, however, comes with an immediate effort cost, r_{work}. On the other hand, the agent remains in the same state with probability 1 on shirking but receives an immediate reward r_{shirk}. The task is a finite horizon problem consisting of 10 timesteps. At the final timestep, there is a utility associated with ending up in each of the three states $\big(r(s_{t=10} = 0) < r(s_{10} = 1) < r(s_{10} = 2) \big)$. A graphical representation of the task can be seen in Figure 3.1a.

For the simulations, the default parameters we use are as follows: efficacy $\eta = 0.6$, horizon $= 10$, terminal rewards for the three states: $r(s_{t=10} = 0) = -4$, $r(s_{t=10} = 1) = 0$, $r(s_{t=10} = 2) = 4$ at the final timestep $t = 10$ and immediate rewards $r_{shirk} = 0.5$, $r_{work} = -0.4$.

3.2.2 Results

Temporal discounting induces a temporal preference for working later

Let us consider the case where $\gamma = 1$. This means that a reward is as valuable later in time as it is immediately, with no reduction in subjective utility with delay. For the assignment submission problem, this means that it is always better to work, unless the efforts are not worth the final rewards, in which case it is better to abandon the task (never work). Initially, there is a slight preference for working over shirking as seen from the Q-values in Figure 3.1b. In the last few timesteps, if the task has not been completed already ($s_t = 0$ or 1), it becomes much better to work so that there is sufficient time left to finish. This is an 'urgency' induced by the deadline. An example trajectory for this case is shown in Figure 3.1c.

When $\gamma = 0.9$, the Q-values change dramatically. Now, there is a temporal preference for shirking earlier and obtaining rewards immediately over working and paying effort costs to secure a distant reward. Hence it is better to shirk in the earlier timesteps and work in the last few timesteps as seen from the Q-values in Figure 3.1d. Figure 3.1e shows an example trajectory where the agent fails to finish on account of starting too late ($s_t = 2$ is not reached by $t = 10$).

Starting times are affected by efficacy

One important parameter is the efficacy – the probability of achieving progress on working. This depends on individual ability as well as the general difficulty of the task. The planned time to start the task (starting times) in each state ($s_t = 0, 1$) shows a U-shaped relation with efficacy as shown in Figure 3.2a. For high efficacy, it is enough to start late while for low efficacy, it is either not worth the effort engaging at all or only engaging towards the end. At intermediate efficacies, it is optimal to start earlier to ensure completion. This pattern is also reflected in the completion rates.

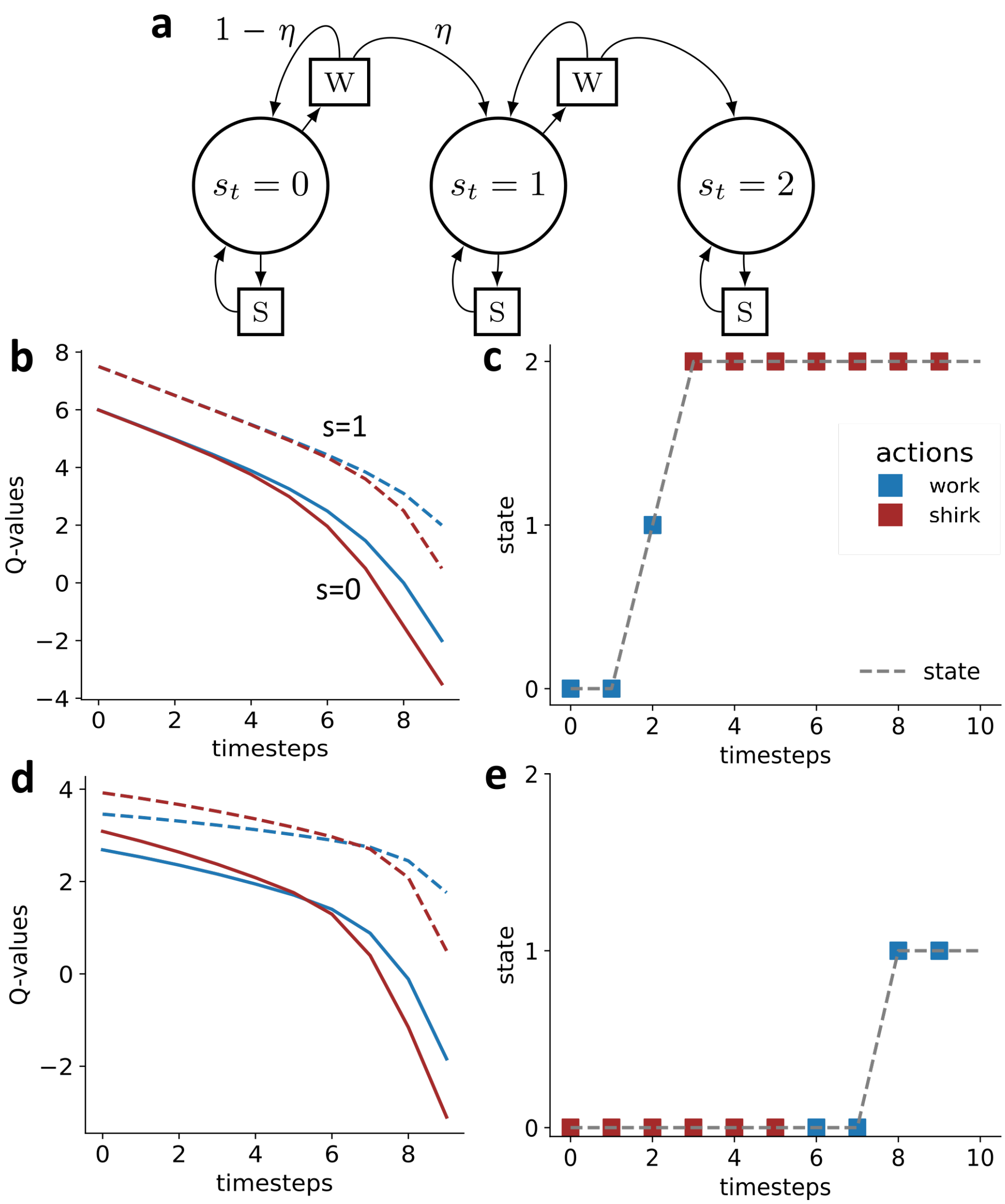

Figure 3.1. a. Schematic of a deadlined, assignment submission problem with three states of completions $s_t = 0, 1, 2$, two possible actions work and shirk $a_t = W, S$. Efficacy $\eta = 0.6$ is the probability of progressing to the next state on working. There are terminal rewards for the three states: $r(s_{10} = 0) = -4$, $r(s_{10} = 1) = 0$, $r(s_{10} = 2) = 4$ at the final timestep $t = 10$ and immediate rewards $r_{shirk} = 0.5$, $r_{work} = -0.4$. b. Q-value for working (blue line) is always better than shirking (red line) when discount factor $\gamma = 1.0$. c. Therefore, the agent first works to complete the task before shirking. d. When discount factor $\gamma = 0.9$, initially, the Q-values for shirking to get immediate rewards is more than working for a distant reward which reverses closer to the deadline. e. Hence, the agent shirks in the beginning and starts working only later on, and so doesn't finish the task (doesn't reach the final state $s_t = 2$).

Completion times and rates can be improved by reducing task effort (aversiveness) or improving rewards on completion

We showed that delays are planned based on estimate of how long it might take to complete the task. Apart from improving efficacy, what can be changed to improve completion times and

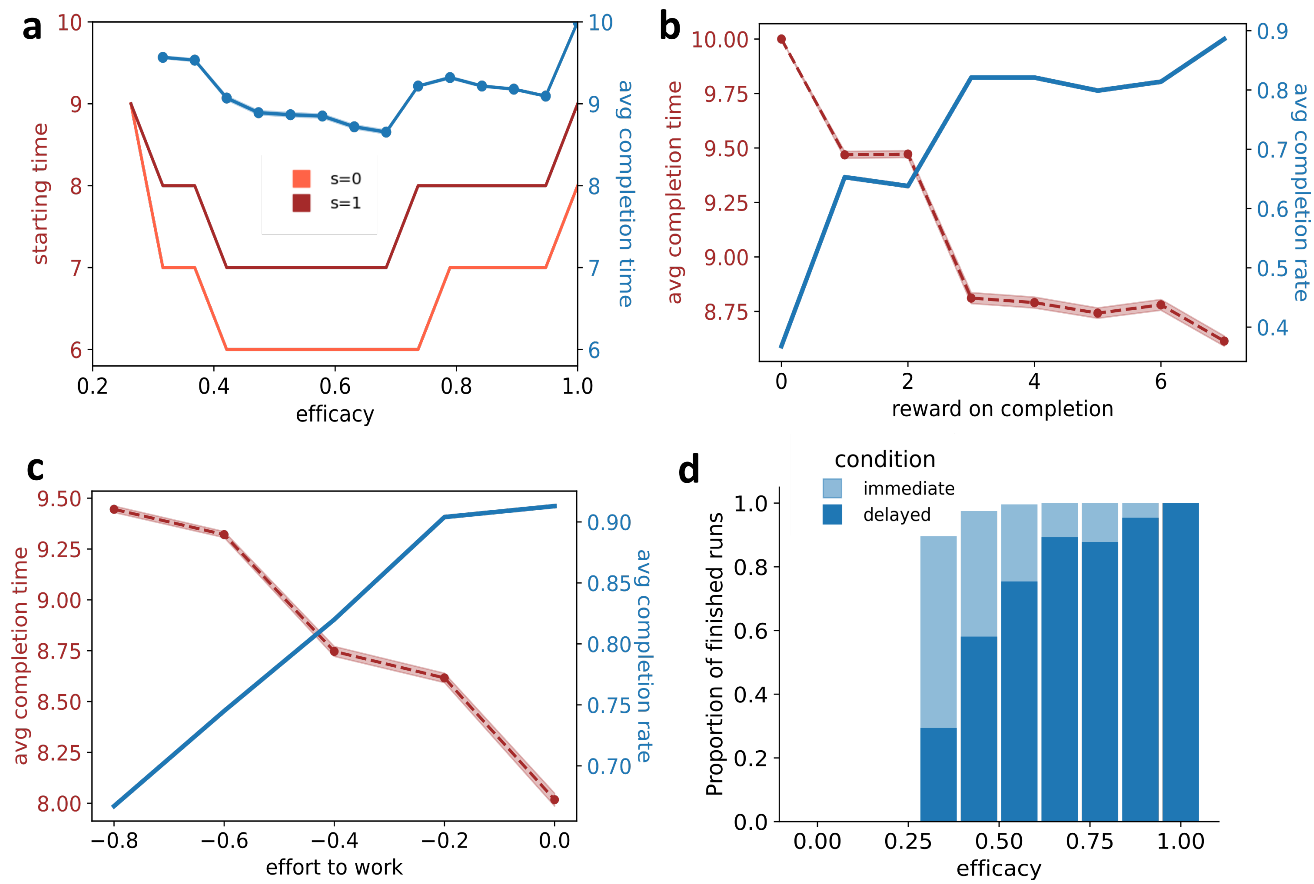

Figure 3.2. a. The planned starting times for states $s = 0, 1$ (peach and red lines) across a range of efficacies (ηs). It is best to start earliest in the intermediate efficacies to ensure completion. For the higher efficacies it is enough to start later and for the lower efficacies it is not worth to start as early. b. Increasing final reward on completion improves completion rates and times. c. Reducing effort magnitude also reduces procrastination and improves completion rates. d. Delivering the reward immediately on completion, instead of at the deadline, eliminates procrastination and improves completion rates across a range of efficacies.

rates? Here, completion time is the timestep when $s_t = 2$ is reached and completion rate is the proportion of tasks that are finished by the deadline, out of the $N = 1000$ simulated.

One possibility is that success on the task is not valued enough for it to be worth more than immediate gratification. This can be due to a gap between personal goals and external expectations: for example, indifference about finishing assignments despite a course instructor's expectations. In our model, increasing the final reward on finishing leads to an increase in completion rates and a reduction in completion times as seen in Figure 3.2b . This is because delays in starting are reduced to improve chances of obtaining the larger delayed rewards. In practice, the increase in final rewards can be in terms of actual, additional rewards like points or prizes, or improved intrinsic motivation from grasping the significance of the task.

Alternatively, the problem can be tackled from the perspective of task effort. If the task is too effortful or aversive, then it becomes worth starting only later in time. Indeed, we find from simulations that reducing effort magnitude improves completion rates and times as shown in Figure 3.2c.

Immediate rewards eliminate procrastination due to discounting

Recall that procrastination in this mechanism comes from preferring instantaneous rewards to delayed ones. The other route to intervention is to then remove these delays altogether and deliver the outcomes immediately on each subsequent stage of completion. This eliminates the delays in starting and consequently improves completion rates across a range of efficacies as shown in figure 3.2d.

3.3 DIFFERENTIAL DISCOUNTING

3.3.1 Set-up

Like we already discussed in Chapter 2, procrastination is also observed in tasks without delays in rewards. Here we discuss one possible route to it, that of differential discount rates for rewards and efforts proposed by (Le Bouc and Pessiglione, 2022). We consider exponential discounts, instead of hyperbolic ones and demonstrate how the presence of different exponential discount rates for rewards vs. costs can give rise to defections through preference reversals.

We consider a task similar to the previous case, just with some minor modifications for simplicity. The task consists of two completion states: start state ($s_t = i$) and final state ($s_t = f$), instead of three. The actions available on every timestep are 'work' ($a_t = W$) or 'shirk' ($a_t = S$), like before. There is also an efficacy (η) and effort associated with doing the task. Finally, the rewards on completing the task (i.e., reaching finish state) come immediately, instead of coming at the end of the task.

For the simulations, the default parameters we use are as follows: efficacy $\eta = 0.6$, horizon $= 10$, reward on completion $r(s_t = f) = 2.0$, efforts for work $r_{work} = -1.0$ and reward on shirking $r_{shirk} = 0$.

3.3.2 Results

Repeated delays from temporal inconsistencies lead to procrastination when efforts are discounted more steeply than rewards

Take the case with the same discount factors for rewards as well as efforts, $\gamma_r = \gamma_c = 0.9$. In this case, as we already discussed in Section 3.2, there is no procrastination at all and it is preferable to work until the task is finished. This is also reflected in the discount curves, where maximum

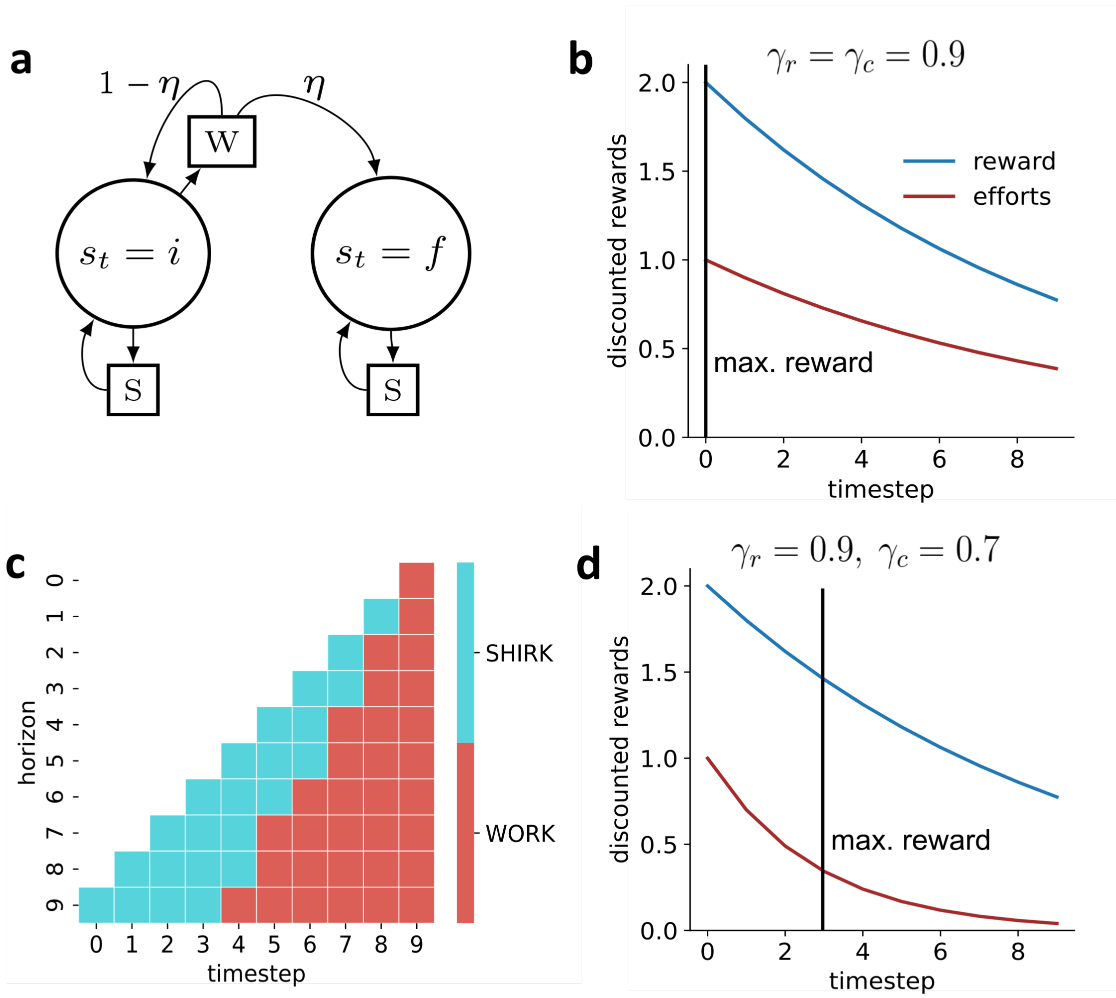

Figure 3.3. a. Schematic of a simplified deadlined, assignment submission problem with two states of completions $s_t = i, f$, two possible actions: work and shirk $a_t = W, S$. Efficacy $\eta = 0.6$ is the probability of progressing to the next state on working. Immediate reward on completion $r(s_t = f) = 2.0$ and efforts for work $r_{work} = -1.0$. b. Discount curves for rewards and efforts, discounted at the same rate $\gamma_r = \gamma_c = 0.9$. The maximum net reward is at $t = 0$. c. When efforts are discounted more steeply than rewards ($\gamma_r = 0.9, \gamma_c = 0.7$), the optimal policy is time-inconsistent. At the beginning when there are 9 timesteps left (horizon$= 9$), it is best to start at $t = 3$ but one timestep later, it is optimal to start even later at $t = 4$ and so on. d. Discount curves for rewards and efforts (discounted more steeply) shows that the maximum net reward occurs a few timesteps away from the present moment.

reward comes from working immediately, shown in Figure 3.3b.

Now, say costs are discounted more steeply than rewards ($\gamma_r = 0.9, \gamma_c = 0.7$). As the discount curves in Figure 3.3d show, the best time to work is actually a few timesteps after the current moment. However, there is another implication with multiple discount factors: the policies are no longer temporally consistent. At $t = 0$, the optimal plan could be to start working 3 timesteps from now. But, at $t = 1$, the plan is to delay working yet again by three steps and so on. The corresponding policy derived for this set of parameters is shown in Figure 3.3c. This is the type of procrastination where plans are reneged on repeatedly, leading to greater delays than initially intended.

A self-control strategy can improve finishing times and rates

These sort of preference reversals are also experienced with any other type of non-exponential discounting. In fact, only single, exponential discount factors are guaranteed to lead to time-consistent policies. Self-control strategies that can counteract these inconsistencies have been discussed extensively in the literature. One strategy is the use of willpower, to simply resist temptations (Ainslie and Haslam, 1992; Mischel et al., 1989). In the case of procrastination, it could mean to resist the urge to defect and act as if the discount factors were equal. Another strategy is pre-commitment where temptations are forestalled so that they do not have to be dealt with later on Ainslie (1974); Crockett et al. (2013). One strategy in our case is to commit to sticking to the initial plan of working at $t = 3$, so that the task is not repeatedly delayed. This actually improves completion times and rates as shown in Figure 3.4a,b.

Steeper discount of rewards compared to efforts leads to unintended engagement in task

Consider again a case where the reward comes at the end of the task (at the deadline). Now, $r(s_{10} = i) = 0$, $r(s_{10} = f) = 4.0$ at $t = 10$ with no immediate rewards on completion. With a single discount factor, we showed in Section 3.2 that it is best to delay to a later timestep, here it is $t = 7$ for $\gamma = 0.9$ displayed by the red line in Figure 3.4c. If $\gamma_c = 0.7$ and $\gamma_r = 0.9$, like before, there are repeated defections on plans until the task is finally started at $t = 8$ as shown in Figure 3.4c. Conversely, if rewards are discounted more steeply ($\gamma_c = 0.9$, $\gamma_r = 0.7$), then there are the opposite kind of reversals where initially, the plan is to abandon the task (never start), then plan to start towards the end (here, $t = 9$) and finally end up doing it even earlier ($t = 8$). This is demonstrated by the trajectory of the light blue line in the same figure. This is structurally a different type of procrastination where one initially plans to abandon a task but ends up doing it later, losing time in the meantime.

3.4 UNCERTAINTY ABOUT TASK DIFFICULTY

3.4.1 Set-up

The next case we consider builds on the task that we have been exploring. Now, there is a possibility that the task is either easy or tough (in terms of the effort required to complete the task). The uncertainty can be resolved by an action of 'check' ($a_t = C$) in the starting state ($s_t = i$) which costs some effort. This action resolves uncertainty about the task difficulty for the agent, and affects a transition to either the easy ($s_t = e$) or hard states ($s_t = h$). These are not real transitions in the world, but can be thought of as subjective transitions in the state of knowledge about the world (resolving the question: is the task easy or tough?) From here, the

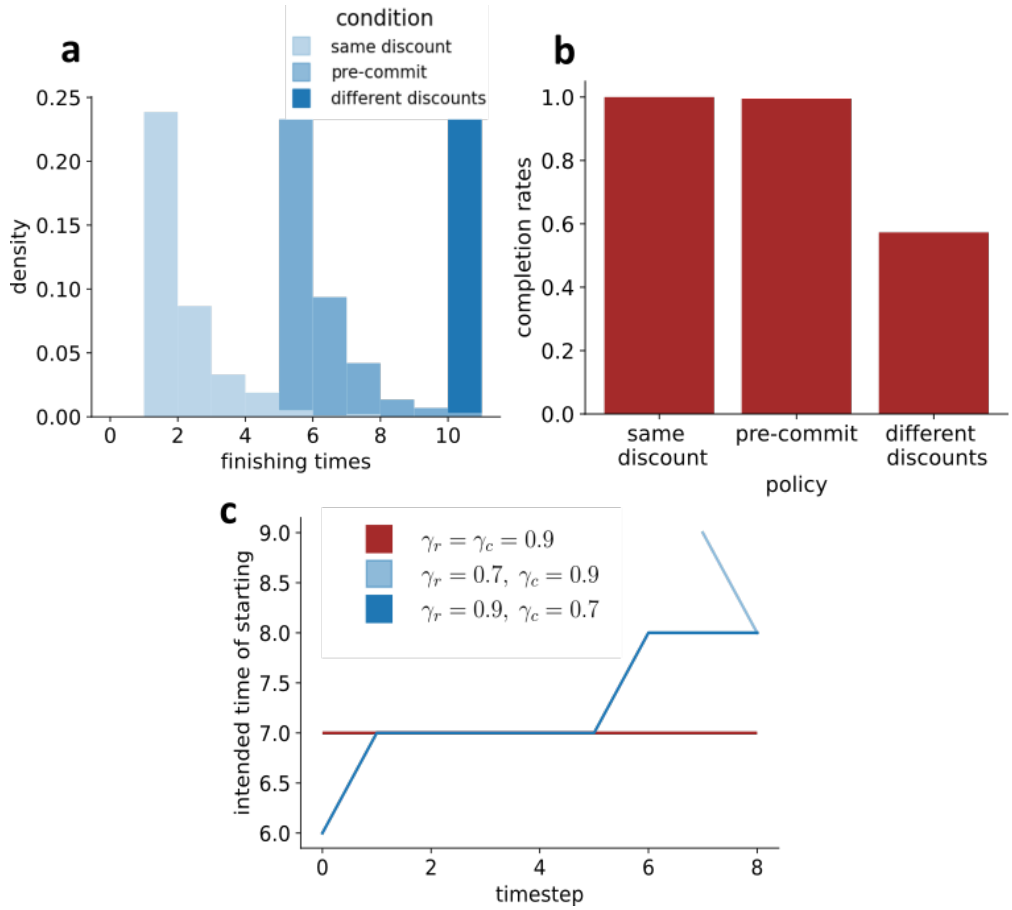

Figure 3.4. a. When efforts are discounted more steeply than rewards, the optimal policy is not consistent in time. Pre-commitment to the optimal policy at the initial timestep prevents defection from inconsistencies and improves finishing times. b. As a consequence, completion rates improve for the pre-commit condition over the regular case. c. When rewards on completion come at a delay, there are similar defections with steeper discounting of efforts. Conversely, when rewards are discounted more steeply ($\gamma_r < \gamma_c$, procrastination comes from abandoning the task at first and then deciding to start later on (shown in light blue).

task proceeds as before: choosing the action of 'work' ($a_t = W$) allows task completion with probability η (efficacy) with some effort costs. In every state, there is an option to 'shirk' ($a_t = S$) which comes with an immediate reward. The task diagram is shown in Figure 3.5a.

For the simulations, the default parameters we use are as follows: efficacy $\eta = 0.6$, probability of task being easy $p_{easy} = 0.9$ (and $p_{hard} = 0.1$), horizon $= 10$, terminal reward on non-completion $r(s_{10} = e, h) = -4.0$ and completion $r(s_{10} = f) = 4.0$ on the final timestep $t = 10$, efforts for checking $r_{check} = -0.1$, work in the easy state $r_{work}(s_t = e) = -0.1$ and hard state $r_{work}(s_t = h) = -2.0$ and reward on shirking $r_{shirk} = 0.5$.

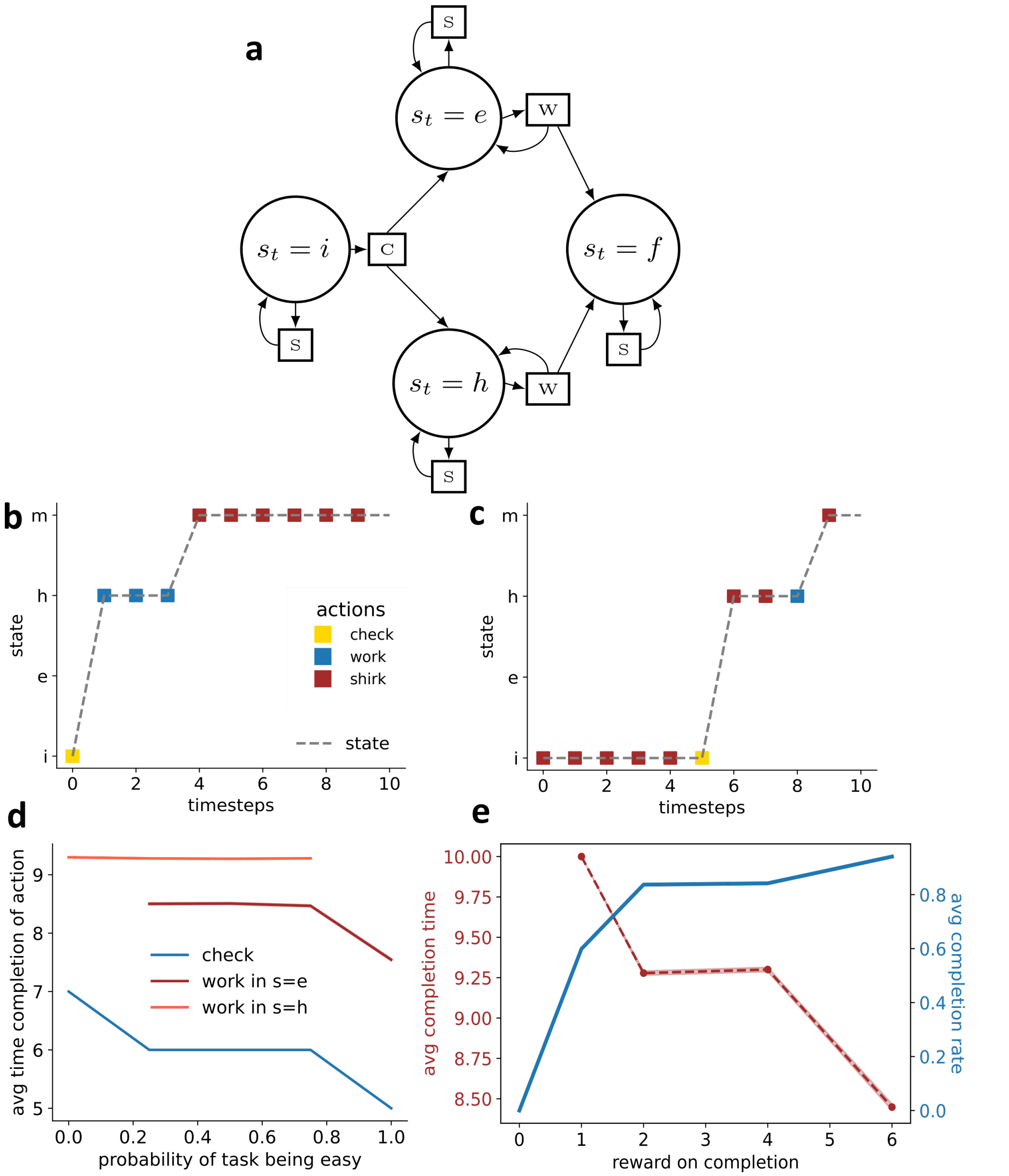

Figure 3.5. a. Schematic of a task where difficulty is uncertain and can be resolved by an action of 'check' ($a_t = C$). The task can either be easy $s_t = e$ or hard $s_t = h$. As before, the agent can either work ($a_t = W$) to finish the task with efficacy ($\eta = 0.6$) or shirk ($a_t = S$). Probability of task being easy is $p_{easy} = 0.9$, terminal rewards $r(s_{10} = e, h) = -4.0$, $r(s_{10} = f) = 4.0$, efforts for checking $r_{check} = -0.1$ and working, $r_{work}(s_t = e) = -0.1$, $r_{work}(s_t = h) = -2.0$ and reward on shirking $r_{shirk} = 0.5$. b. Without delay discounting $\gamma = 1$, checking and working is done promptly without delays. c. With $\gamma = 0.9$, there are delays in checking and working which have immediate efforts but delayed rewards. Since the probability of task being tough is low ($p_{hard} = 0.1$), there is a further delay after checking. d. The gaps between checking and working in $s_t = h$ increase with the probability that the task is easy. When the task is most likely easy, it is better to check early to work early. But on the unlikely instances that the task is tough, there are apparent defections to delay working. e. Increasing rewards on completion improves completion rates and times.

3.4.2 Results

Discounting leads to delays in checking and working

With $\gamma = 1$, as in Section 3.2 on the basic temporal discounting case, it is always better to work given sufficient final rewards. An example trajectory is shown in Figure 3.5b.

When $\gamma = 0.9$, it becomes optimal to delay working in both the easy and hard tasks for the same reasons as in Section 3.2. The extent of the delays depends on the size of the efforts in each of the states. There is now a similar delay in checking how difficult the task is, since it seems more attractive to shirk than put in the effort to check earlier on. The extent of the delay is modulated by the probability of the task being easy vs. tough, the efforts required to work in these states, efficacy etc. In this case when the task is most likely easy ($p_{easy} = 0.9$), it is better to check early so that if the task turns out to be easy, it can be finished promptly. In the unlikely case that the task proves to be tough, it is optimal to go back to shirking until it is worth it to work again. These are apparent 'defections' that arise from unlikely appearances of a tough task. An example trajectory is shown in Figure 3.5c where the task is not completed due to starting too late.

Gaps between checking and working increase with probability that the task is easy

The gaps between checking and working in the tough state widen with probability that the task is easy. This can be seen in Figure 3.5d. When the task is already expected to be easy, checking is done more promptly since the tough state is unlikely. On the other hand, with lower probabilities that the task is easy, checking is also delayed more. Therefore, the gap between checking and working in the tough state reduces.

Completion rates and times can be improved by increasing reward

As before, raising the final reward at stake can reduce delays and accordingly improve completion rates, as seen in Figure 3.5e. When the task is valued enough, checking and working are not delayed as much.

3.5 WAITING FOR FAVOURABLE CONDITIONS

3.5.1 Set-up

In our taxonomy in chapter 2, we discussed some plausible explanations for delaying that are not due to discount factors. We explore one of them, where there is a probability that task difficulty changes independent of the actions of the agent. This can happen due to internal reasons like improved skill levels, better knowledge or changing mood on the part of the agent or, external changes in environment like changes in weather or working conditions. Here, we consider three states, easy ($s_t = e$), medium ($s_t = m$) and hard ($s_t = h$), that are associated with different efforts required to complete the task. There exists a probability of transitioning between these states, not in control of the agent. As before, the agent can either 'work' ($a_t = W$) or 'shirk' ($a_t = S$), with similar transition and reward functions associated with them.

For the simulations, the default parameters we use are as follows: efficacy $\eta = 0.7$, horizon $= 10$, discount factor $\gamma = 1.0$, efforts for working in the three states easy, medium, hard: $r_{work}(s_t = e) = -0.2, r_{work}(s_t = m) = -0.5, r_{work}(s_t = h) = -1.2$, terminal reward on non-completion $r(s_{10} = e, m, h) = 0.0$ and completion $r(s_{10} = f) = 4.0$ on the final timestep $t = 10$ and reward on shirking $r_{shirk} = 0.5$. The action-independent transition probabilities between the three difficulty states is given by:

$$T = \begin{array}{cc} & \text{Next State} \\ & \begin{array}{ccc} \text{e} & \text{m} & \text{h} \end{array} \\ \text{Current State} \; \begin{array}{c} \text{e} \\ \text{m} \\ \text{h} \end{array} & \begin{bmatrix} 1.0 & .0 & .0 \\ .05 & .95 & .0 \\ .0 & .05 & .95 \end{bmatrix} \end{array}$$

This means that for an agent that starts out in tougher states, there is a small probability that the task might get easier. That is, states requiring less effort to finish might be reached. This can be interpreted as an improvement in skills or knowledge with time, for example.

3.5.2 Results

Waiting for better conditions leads to delays

Say that there is no transition probability to other difficulty states, i.e, $T = \mathbb{1}$ (identity). Then, without any discounting, there is no reason to delay. This means that it is always better to work in any of the difficulty states until the task is finished, if it is worth the effort as seen in Figure 3.6b.

On the other hand, when there is a sufficient probability that the task can actually get easier (as in the default transition matrix), it becomes optimal to wait for the easy state to come up if the task is currently tougher. This is so that the task can be completed with less effort. However, given that the task takes a finite time to complete, there is a limit to waiting. If the anticipated easy state doesn't come up beyond this limit, it is better to work even in the tougher states to finish the task as demonstrated in Figure 3.6c. So for example, if the agent begins in $s_t = 2$, it is optimal to shirk and wait for an easier state. If it finds itself still in the hard state $s_t = 2$ at $t = 6$, then it is better to work and finish the task.

The distribution of completion times for the two types of transition dynamics are shown in Figure 3.6d. When $T = \mathbb{1}$, the task is completed promptly but with the default transition probabilities, there is more procrastination due to waiting and the distribution is shifted to longer times.

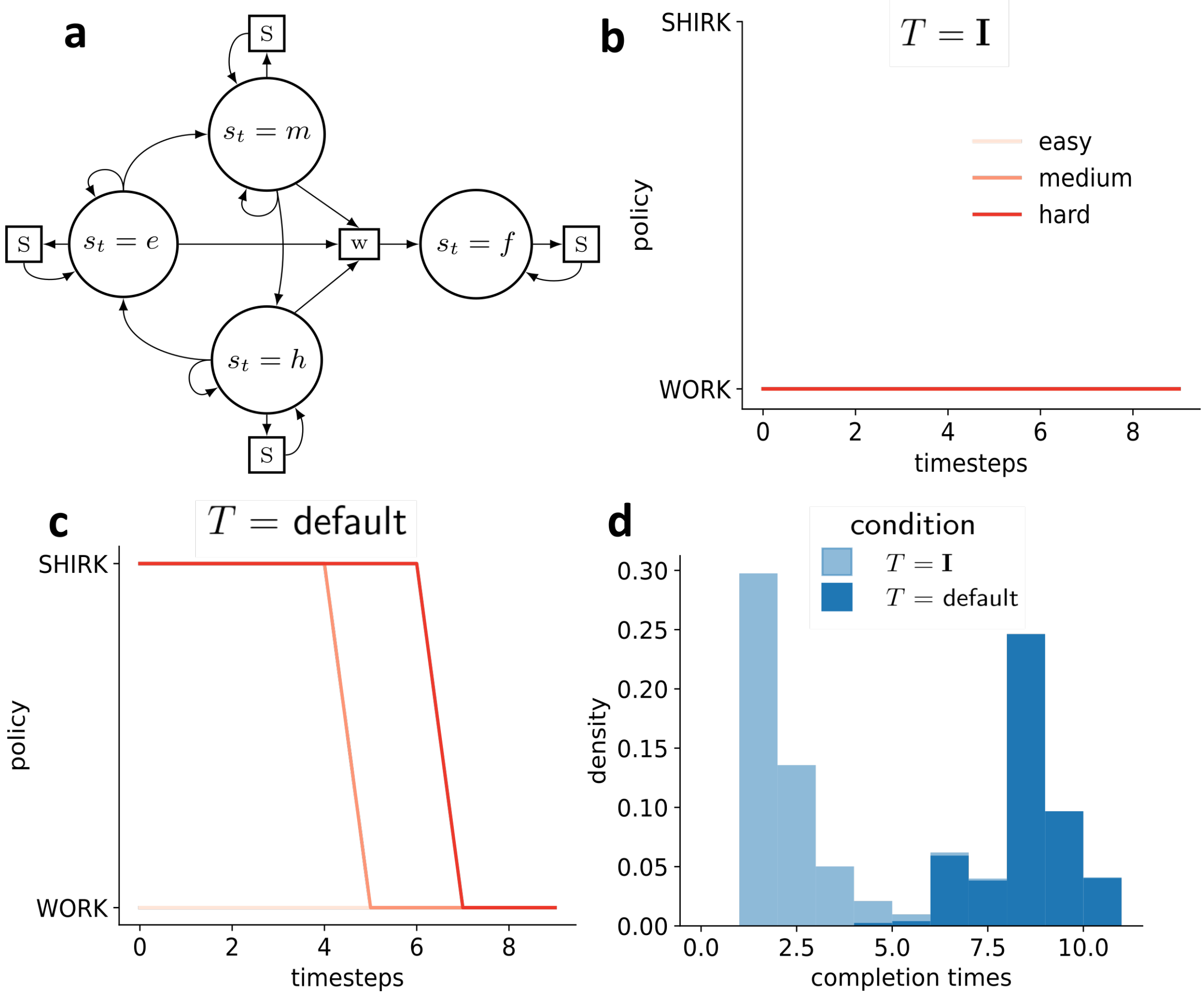

Figure 3.6. a. Schematic of a task where difficulty changes with time, independent of the actions of the agent. The difficulty states are easy ($s_t = e$), medium ($s_t = m$) and hard ($s_t = h$) associated with different efforts of completing the task: $r_{work}(s_t = e) = -0.2, r_{work}(s_t = m) = -0.5, r_{work}(s_t = h) = -1.2$. Final state $s_t = f$ can be reached by working with efficacy $\eta = 0.6$. Terminal rewards are $r(s_{10} = e, m, h) = 0.0$ and $r(s_{10} = f) = 4.0$. Immediate reward for shirking are $r_{shirk} = 0.5$. b. When probability of transitioning to other states is 0, there are no delays in working. c. Even with a small probability of task getting easier in the tougher states, it becomes optimal to wait for an easier state to come up (here, $t = 5, 7$ for states $s_t = m, h$). d. Due to delays from waiting (non-committing), finishing times are higher than without waiting

Completion rates and times can be improved by increasing relative reward for finishing the task

As before, the issue might simply be that the reward on completion is deflated, so that it is optimal to risk non-completion if it means the task can be completed for cheaper. Figure 3.7a shows that as the reward on completion is made larger, the completion rates and times improve. It is not worth waiting as long for a better state to arrive anymore.

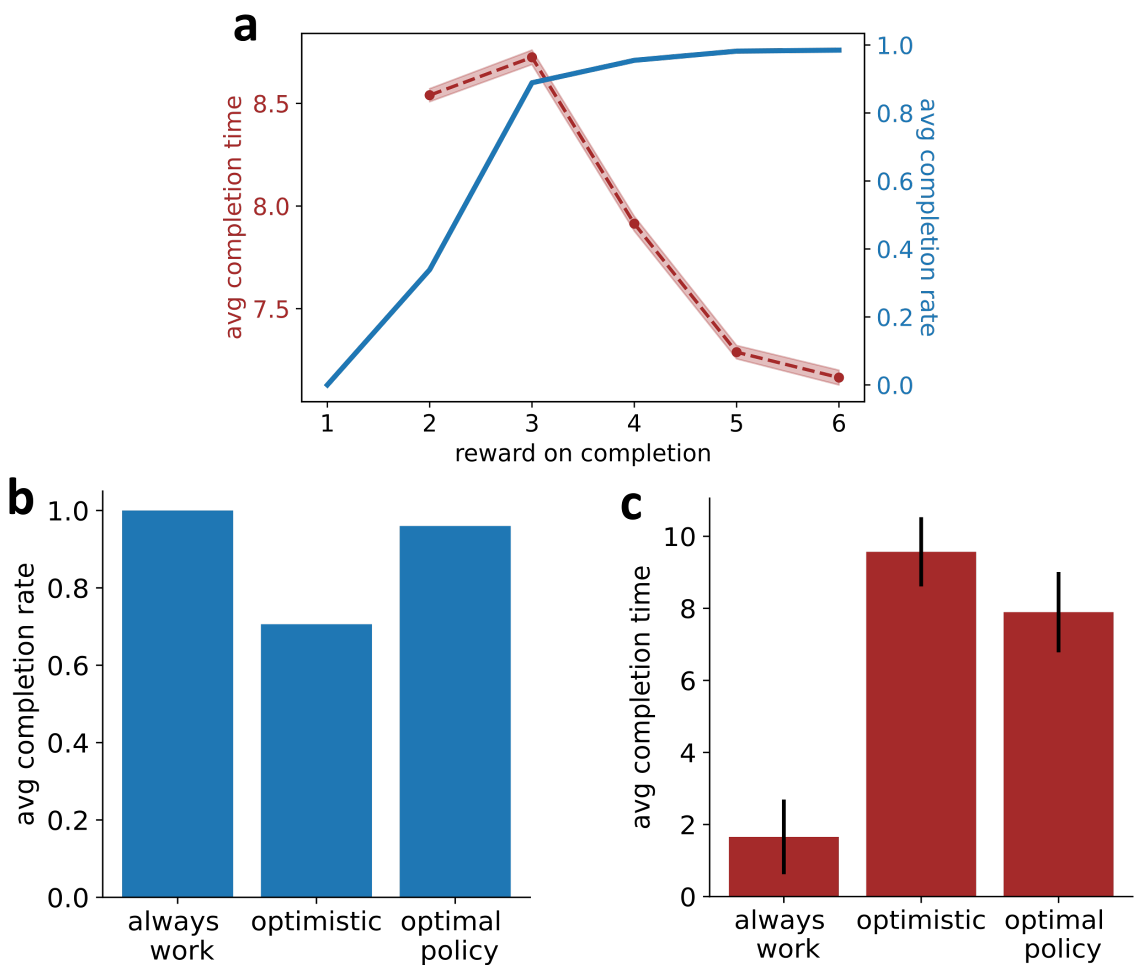

Figure 3.7. a. Increasing rewards on completion improves completion rates and times because it becomes less worth it to risk non-completion by delaying. b. When the agent assumes a much greater probability of task getting easier when starting at tougher states than reality (agent is 'optimistic'), there are longer delays and hence completion rates are lower. c. The longer delays are reflected in the larger completion times.

Mismatched models of the world lead to procrastination

Another possibility is that there is a gap between the real transition dynamics of the world and what the agent assumes. For example, it might be slow to gather new skills, but the agent falsely thinks that it is more likely within the time-frame of the task. This over-optimism might lead to greater delays and lower completion rates. We simulate this scenario by setting the real transition matrix to default, where there is a small probability of improving. The agent, however, assumes the an 'optimistic' transition matrix where there is a much greater possibility of improvement:

$$T = \begin{array}{c c} & \text{Next State} \\ & \begin{array}{ccc} \text{e} & \text{m} & \text{h} \end{array} \\ \text{Current State} \begin{array}{c} \text{e} \\ \text{m} \\ \text{h} \end{array} & \begin{bmatrix} 1. & .0 & .0 \\ .9 & .1 & .0 \\ .0 & .9 & .1 \end{bmatrix} \end{array}$$

Figure 3.7b shows that this wrong assumption leads to smaller completion rates (when task starts at $s = h$) in the 'optimistic' condition compared to the optimal policy (calculated from the correct T) as well as the condition where there is no delay at all ('always work'). This due to greater delays in the 'optimistic' condition as shown by the average completion times in Figure 3.7c.

3.6 WAITING FOR INFORMATION

3.6.1 Set-up

Finally, we consider a case where there is uncertainty about whether the task can be improved before submitting it, which is an irreversible action. Submission of assignments or submitting research papers to journals or conferences are a few examples of such a situation. We can formulate this problem with an initial state ($s = i$) where one can work to progress exactly as in the previous cases. This effects probabilistic transitions to one of two intermediate states from where there is either a probability to improve or not. This means a choice to 'work' ($a = W$) in one of the intermediate states ($s = 0$) does not improve the state any further, while there is a chance for betterment in the other state ($s = 1$), which when succeeded effects a transition to the improved, completely observable final state, ($s = f$). Critically, these states are partially observable, so the agent can not be sure whether an assignment can indeed be improved. This uncertainty can be stochastically resolved by a 'check' action ($a = C$) at some cost. Once the agent decides to 'submit' ($a = Su$), the trial ends. For simplicity, we don't include the initial state ($s = i$) in our simulations and instead, there is simply a prior probability over which of the two intermediate states the trial starts in.

This problem is set-up as a POMDP whose general solution we discussed in Section 3.1 on methods. For the simulations, the default parameters we use are as follows: efficacy $\eta = 0.6$, indefinite horizon, discount factor $\gamma = 1.0$, observation noise on checking $= 0.3$ (for other actions, the observation noise is 0.5), reward on submission in each of the states are $r(s = 2) = 5.0$ and $r(s = 0, 1) = 0.0$, effort to work is $r_{work} = -1.5$ and effort to check is $r_{check} = -0.1$.

3.6.2 Results

Sampling for information leads to delays

The policy is now on the (1-dimensional) belief-space which we index by the probability that the hidden state is 1 ($p(s = 1)$). The policy for the default set of parameters is shown in Figure 3.8b. When one is relatively certain that improvement is possible ($P(s = 1) > 0.85$), it is best to work; it is better to just submit if is most likely that it cannot be improved upon ($P(s = 1) < 0.2$) and for intermediate possibilities, the best option is to check to gain more information. Starting at

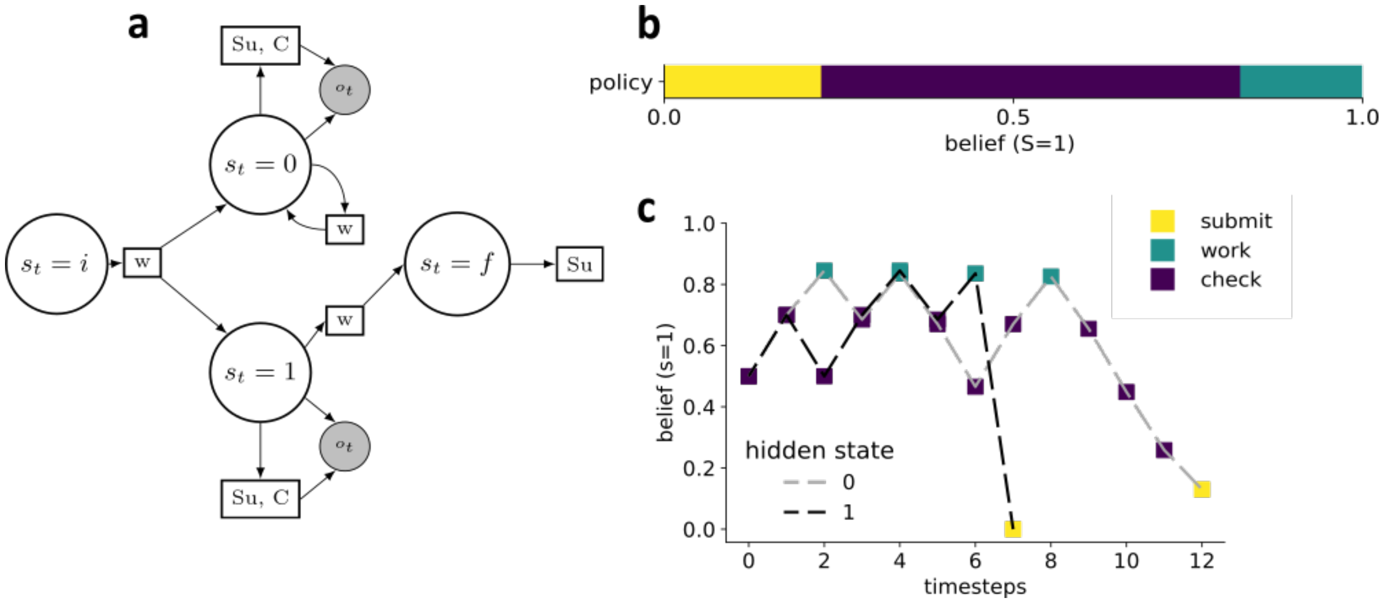

Figure 3.8. a. Schematic of a task where there is an uncertainty about whether the task can be improved before submission. From $s = 0$, it can not be improved while from $s = 1$, it can be improved by working with efficacy ($\eta = 0.6$). $s = 0$ and $s = 1$ are partially observable and uncertainty can be resolved by 'checking' $a = C$. Observation noise on checking $= 0.3$ (for other actions, the observation noise is 0.5), rewards on submitting are $r(s = 2) = 5.0$ and $r(s = 0, 1) = 0.0$, effort to work is $r_{work} = -1.5$ and effort to check is $r_{check} = -0.1$. b. The policy is on the belief space that $s = 1$. When $P(s = 1) > 0.85$, it is best to work; when $P(s = 1) < 0.2$, it is best to submit; and otherwise, it is best to check to reduce uncertainty. c. Example trajectories when the hidden state is $= 0$ and $= 1$. Submission on the task is delayed until enough information has been collected.

an intermediate prior probability (here, $P(s = 1) = 0.5$), it takes some time to sample enough information to be sure enough to submit the work. In Figure 3.8c, we show example trajectories when the initial hidden state is $s = 0$ and 1. This is the type of procrastination where delays are not fixed at the start but occur due to waiting for more information ('non-committing').

Length of delays is affected by magnitude of rewards, efficacy and observation noise

The extent of delays in this task is modulated by the efficacy, observation noise and size of final rewards as shown in Figure 3.9a-c. When efficacy is high, it doesn't take very long to improve or realise that this is not possible. On the other hand, for very poor efficacies, it is less and less worth it to even try. Therefore, the longest delays occur at intermediate efficacies (Figure 3.9a). A similar pattern occurs with observation noise, where it doesn't take long to determine the real state when noise is small and it is not worth checking for very noisy states. The longest delays, hence occur with intermediate noise levels (Figure 3.9b). Finally, increasing the final rewards makes it better to wait for more information before irreversibly submitting. Underestimating the importance of the task (smaller final rewards) can actually lead to 'precrastination' where work is submitted hastily, hence missing out on the reward at the end as shown by the completion times and rates in Figure 3.9c. On the other hand, overestimation of the importance of the task (larger final rewards) or perfectionism can lead to procrastination where submission is unnecessarily put off. Figure 3.9c shows that the completions rates don't improve as much by waiting more and more (due to higher rewards).

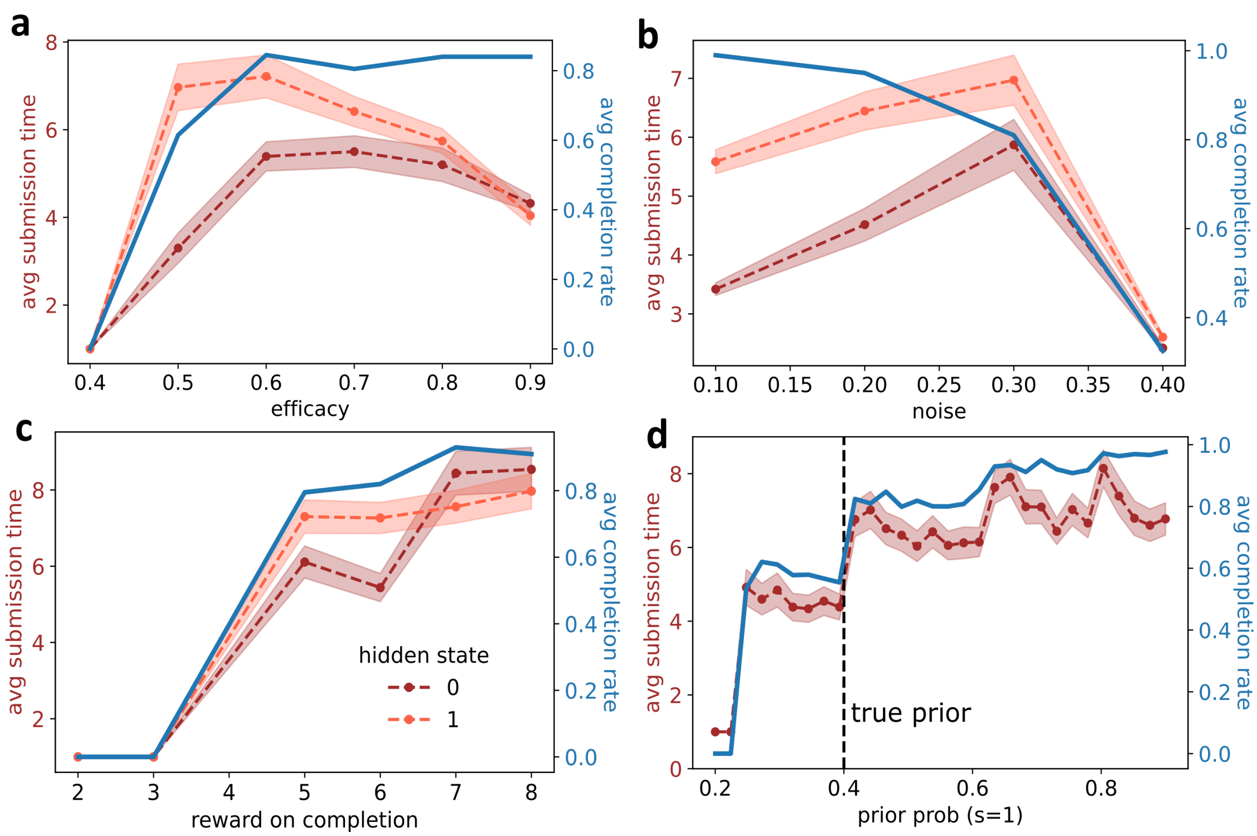

Figure 3.9. a. Submission times are the longest for intermediate efficacies and b. for intermediate noise. At higher efficacies and smaller noise, it doesn't take much time to realise the true state and at lower efficacies and larger noise, it is not worth checking for long. c. When reward on completion is very high, submission times and consequently completion rates increase. d. With gaps between true prior and the assumed prior of the agent, the task either precrastinated or procrastinated. Here, procrastination improves finishing rates but the possibility of improvement (that is, $s = 1$) is not as high as the agent assumes.

Mismatched priors lead to greater procrastination

Another route to procrastination can be from a mismatch between assumed and real prior probability that the task can be improved. In Figure 3.9d when the real prior is $P(s = 1) = 0.4$, underestimation leads to precrastination where assignments are submitted early which leads to smaller completion rates. On the other hand, overestimation leads to greater delays but also greater completion rates.

4 DISCUSSION

In this work, we presented a taxonomy of types of procrastination based on the structure of the delays and suggested a classification of mechanisms that might underlie these different type of delays. We simulated some of these mechanisms in the MDP and POMDP frameworks, highlighting the core elements and some possible interventions. We end with a discussion about how our insights compare with past literature, some of the advances we made, and finally, future directions to explore.

Our first contribution is a taxonomy of procrastination types and the routes to it. The existence of different types of procrastination is widely debated in the literature. We have argued and shown through simulations that a variety of different mechanisms can lead to different structures of delays, in theory. In fact, an earlier, influential theory proposed arousal, avoidant and decisional forms of procrastination (these are delays for thrills, putting off aversive outcomes and procrastination of decisions respectively) (Ferrari, 1992). There has been conceptual pushback from some quarters against the idea that purposeful delays to protect self esteem or decisional avoidance even constitute procrastination (Anderson, 2006; Steel, 2010). This camp prefers to refer only to irrational delays (despite knowing otherwise) as procrastination. At the same time, there has been a resurgence of the concept of 'active' or 'intentional' procrastination which are delays meant to optimise performance associated with desirable outcomes and satisfaction. We argue instead that procrastination can come from uncontrollable, irrational delays or from rational reasons which might still lead to missing of deadlines or unsatisfactory performance. This is reminiscent of the distinction between abnormalities stemming from solving the wrong problem correctly vs. solving the right problem poorly in Computational Psychiatry (Huys et al., 2015). The first kind are like rational procrastination where there might be a gap between the utility function of the subject and external expectations, leading to procrastination. The latter are like the traditional, irrational conceptions of procrastination.

The other contribution of this work is a demonstration of the operation of some of the mechanisms proposed by others and ourselves. Our model based approach to modelling decision making has key advantages over past studies. It provides a systematic method to formalise temporal decisions to delay and derive optimal behavior. For example, the temporal motivation theory (TMT) predicts that in tasks where rewards come at a delay, delays should increase with lower efficacies due to lower motivation (Steel and König, 2006). However, taking into account the time it takes to finish the task (which is a function of efficacy) would dictate that one start earlier to ensure completion, as our model predicts. In general, we do not make assumptions about the rule to begin working, rather this is easily derived from the optimal policy. Of course, it remains to be seen whether people actually behave as predicted by our account, but it still provides a normative standard to compare against.

Past studies have highlighted the importance of elements like reward type, timings, delay and time pressure (Steel, 2007). In addition to these elements, we also explored the overlooked element of uncertainty about task characteristics like reward or effort magnitude and timings or current state. We showed that attempts to resolve the uncertainty by collecting information or waiting for uncertain events to occur are possible reasons for procrastination. For mechanisms depending on discounting, it is standard to use hyperbolic discount factors since this has been found to be the best-fitting curve (Green et al., 1994). We however use exponential discount factors since the MDP framework depends on a time-consistent discount factor. While this was largely for convenience, it also offered us the advantage of disambiguating the effects from devaluation with delay found with any discounting curve vs. preference reversals from non-exponential discount factors. We demonstrated the latter using different exponential discount factors for rewards and efforts for which there is some evidence (Le Bouc and Pessiglione, 2022; Shu and Gneezy, 2010). In fact, any type of discounting that doesn't involve just a single exponential discount factor will show these type of temporal inconsistencies.

We proposed a variety of plausible mechanisms classified by the type of procrastination they lead to, many independent of and non-collapsible to temporal discounting. It is illustrative to reconsider these mechanisms in the light of empirically found personality correlates. Temporal discounting is the obvious candidate for the correlations found with impulsivity and distractibility among procrastinators – steeper discount functions could make one more distractible. Action-intention gaps, the lack of self-control and organisation could correspond to the effects of preference reversals and a deficit of will, planning and other strategies that counteract these reversals. The lack of achievement motivation could imply that a task is not valued enough which generally exacerbates procrastination across a range of mechanisms that we demonstrated. Elements of sensation-seeking and arousal can underlie the voluntary decisions to delay for thrills or the efficiency from increased time-pressure or perhaps even savoring from delays. Traits of low self-esteem, fear of failure and self-handicapping can correspond to the mechanisms of delaying engagement to avoid finding out about potential inability, ego-protection and dread. Tendency to hold irrational beliefs about ability and task difficulty, perfectionism etc. may map onto miscalculations about how tough the task can be or how much better one can be at it, overestimation of the amount of skills that can be gathered etc. Other explanations might depend more on the features of the task itself rather than personality traits, like the resolution of any uncertainty present or the occurrence of unexpected events or changes.

Having established the possibility of a variety of mechanisms, a natural question to ask is whether these truly exist and how they can be detected. It is becoming increasingly popular to use natural tasks like submission of assignments and forms to detect causes for procrastination (Le Bouc and Pessiglione, 2022; Lieder et al., 2019; Steel et al., 2018; Zhang and Ma, 2023).

We suggest some possible experiments that can make the estimation of models easier, based on our simulations. One suggestion would be to vary the type and structure of tasks since the exact mechanism depends heavily on these. It would be interesting to assess procrastination in different scenarios like signing up for a gym membership, submitting important forms like tax filing, submission of research papers, making an appointment to the dentist, prepare for a talk etc. This also allows to investigate situations which come with deadlines and others that don't. Some of them come with an opportunity to improve skills or knowledge with time, others come naturally with uncertainty about outcomes or task state. It would be crucial to measure or quantify these components. It is also important to separate the delay in reward and the deadline itself to distinguish their effects. Further, in order to assess the structure of the delays, it could be helpful to measure when people intend to do a task vs. when they end up doing it and if they had a plan for when to engage in the task from the start. These can come from an ecological momentary assessment that allows measurement of behaviors in real time (Shiffman et al., 2008). A downside of such experiments is that these questions may induce demand characteristics in the participants. Retrospective questions can also be asked about reasons for non-completion, specific anxieties regarding the task etc. Finally, objective measures of procrastination should reflect the definitions of the concept. This implies that simply measuring delays is insufficient but one must also measure the effects of the delays – inability to complete, unsatisfactory performance or wasted time.

We also touched upon some possible interventions to alleviate procrastination from our simulations. One general method that we encountered repeatedly is simply to value the task more so that one cares enough to finish it early enough. Obvious ways can be extra points or money (Lieder et al., 2019) but other ways can be pairing immediate rewards or making the gravity of non-completion in the task explicit. Another possible intervention was to reduce the effort or aversiveness of the task. Some methods suggested previously for this were to make a task more interesting by ensuring it is not too simple (Wright et al., 1995), conditioning so that the effort to reach a goal itself becomes reinforcing (Eisenberger, 1992), etc. Cultivating self-control and adopting pre-commitment techniques like making it harder to access temptations are other ways (Ainslie and Haslam, 1992). Other methods might be to remedy the gap between the real and assumed task characteristics, be it a mis-estimation of how tough the task is, how much one can get better at it, how likely it is that one's work can be improved upon, etc. These wrong estimates could have been learnt from unfortunate experiences that may no longer hold or genuine miscalculations like in other psychiatric conditions (Huys et al., 2015). Here, ideas from computational, learning-based psychotherapies can be used to nudge procrastinators towards the correct beliefs (Moutoussis et al., 2018). Finally, these interventions can have unintended consequences and so must be applied carefully. For example, one method we discussed to improve motivation to do the task was to communicate the gravity of not completing it. This could also have the effect of inducing dread and aversiveness towards working on the task, and could inadvertently lead to more procrastination.

Finally, there are some drawbacks in our approach. We employ discrete-time MDPs which means there is a loss of resolution in functions of time. Semi Markov decision processes that work in continuous-time might instead be more appropriate (Hu and Yue, 2008). We derive optimal policies for the mechanisms assuming knowledge of task structure and contingencies. However, these aren't necessarily how they are arrived upon in reality. Further, the policies are not updated from experience in our simulations which could allow correction of mis-estimates and wrong assumptions. We set the policies to be completely deterministic. In practice, policies are most likely probabilistic, allowing exploration. In addition, we introduced a number of mechanisms in the taxonomy of routes to procrastination that we did not explore in detail with modelling due to limited time (like arousal, avoiding information due to dread, negative discounting, etc.)

In the future, it will be interesting to simulate these other mechanisms. We would also like to extend the simulation of preference reversals to the infinite horizon. In addition, we will explore the operation of learning mechanisms that might reinforce delays for example due to relief, reinforcement of thrills from delays or self-fulfilling predictions about ability. Oppositely, there can also be error-correcting mechanisms at play that could naturally steer one away from incorrect assumptions. It is crucial to check if these theoretically outlined types can be found empirically from real-world procrastination tasks and which of the plausible mechanisms actually explain delays. There could be challenges in disentangling the effects from different sources and credit assignment to the appropriate mechanism. Finally, we would also like to understand what mediates regret, worry or even positive metacognitive beliefs about procrastination and how they in turn modulate delays (Fernie et al., 2017; Zhou et al., 2022).

In conclusion, procrastination is a complex and multidimensional phenomenon that we have only begun to understand. Perspectives and techniques from diverse fields of thought are vital to construct a complete theory of procrastination.

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