Projection Bias in Effort Choices*

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Abstract

Working becomes harder as we grow tired or bored. I model individuals who underestimate these changes in marginal disutility – as implied by "projection bias" – when deciding whether or not to continue working. This bias causes people to fluctuate between planning to work too little when tired and to work too much when rested; and to smooth required work too little over time due to underestimating changes in marginal disutility. Despite the fluctuations, people with increasing marginal disutility facing a single task with decreasing returns to effort work optimally. However, at all times they overestimate how much they will work later that day after growing tired. Thus, when facing multiple tasks, people misprioritize urgent but unimportant over important but non-urgent tasks. When they face a single task with all-or-nothing rewards (such as being promoted) they start, and repeatedly work on, some overly ambitious tasks that they later abondon. Each day they stop working once they have grown tired. No matter how small the bias is, this can lead to large daily welfare losses. Because people, rested or tired, underestimate changes in marginal disutility, they overreact to differences in incentives, opportunity costs, and productivity. Both when productivity is decreasing or increasing, together with fluctuations this leads people to work less each day than previously planned. By working less than planned, people move closer to optimal effort for decreasing, and further away from optimal effort for increasing productivity.

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1 Introduction

Our tastes fluctuate, often rapidly: we grow tired and thirsty from running, and we savor food or crave coffee more the longer we go without. Furthermore, evidence from a variety of domains suggests that our perceptions of our tastes are biased toward our current tastes: we misperceive future tastes as being closer to our current tastes than they will be (Loewenstein, O'Donoghue, and Rabin (2003)).[1] This *projection bias* can trigger undesirable and unintended habits and behaviors, such as buying too much when shopping on an empty stomach, or becoming addicted due to under-appreciating the future intensity of cravings. In this paper, I study effort choices where the distaste for work fluctuates, such as when students grow bored of studying or employees become tired of working. Due to projection bias, individuals mispredict future disutility of work, which can cause them to mis-prioritize between tasks, waste time on never-to-be-completed tasks, and inefficiently choose when to work on those tasks.

I describe the model in Section 2. At every moment of the day, the agent either works or does not work and is self-directed: she works if and only if at that moment she perceives it as worthwhile to continue working.[2] Whether she decides to work depends on her actual disutility, her future disutility as she perceives it, and the benefits she faces, each of which I describe in turn. Her instantaneous disutility changes over the course of the day: letting S denote the total time she has worked so far that day, instantaneous disutility is equal to $D'(S)$, where $D(\cdot)$ is the total *daily* disutility. Unless stated otherwise, the marginal disutility $D'(\cdot)$ increases – the person grows more tired and bored the longer she works. In this setting, projection bias implies that a person projects her current marginal disutility: she predicts that her marginal disutility after E hours of work on any day lies between her current marginal disutility, $D'(S)$, and her true marginal disutility, $D'(E)$. Finally, every task she faces has either decreasing (or constant) marginal benefits or all-or-nothing benefits, in which case she receives known, fixed benefits if she completes the task by the end of a given day.

A projection-biased person makes two mistakes. First, her plans fluctuate with her tiredness: when she is rested and marginal disutility is thus particularly low, she overestimates how easy it will be to work, while when tired and marginal disutility is thus particularly high, she underestimates it. These inconsistent plans can lead to time-inconsistent behavior: she starts some overly costly all-or-nothing tasks, but as work becomes more unpleasant, she realizes some of the higher costs

[1]Evidence for projection bias has been found for food (Read and Van Leeuwen (1998); Nordgren, Pligt, and Harreveld (2008)), drink (Van Boven and Loewenstein (2003)), sexual arousal (Loewenstein, Nagin, and Paternoster (1997); Ariely and Loewenstein (2006)), effortful tasks (Augenblick and Rabin (2019)), heroin substitute cravings (Badger et al. (2007)), the endowment effect (Loewenstein and Adler (1995)) and for predictions of gym attendance (Acland and Levy (2015)). Projection bias resembles immune neglect (Gilbert et al. (1998)) whereby people overestimate how long they will feel bad about negative events.

[2]I discuss irreversible choices in passing. Since a projection-biased person has no desire to commit, there is no reason why a particular plan should overrule her current plan – except in situations where a principal might demand that she commit.

and may give up. For single-period tasks, she would be worse off if she stuck to her original plan. Second, any given plan underestimates the benefits of smoothing effort: when she is tired, she underestimates how easy future work will be; and when rested, she overestimates how easy future work will be. In both case, this causes her to be less willing to reallocate effort from periods where work is harder to where work is easier. This magnifies the impact of incentives, opportunity costs, or productivity across days on effort allocation across days, and magnifies existing time preferences and time inconsistencies.

In Section 3 and 4, I analyze the implications of fluctuations between over- and underestimating the disutility of future work. In Section 3, I consider several reward structures for single-day settings, when all tasks are due at the end of that day. Because a person grows tired the longer she works, she underestimates how unpleasant the work will be later that day and overestimates how much she will work. With all-or-nothing rewards, a projection-biased person starts some overly ambitious tasks, only to abandon them later. Despite this, with decreasing returns to effort, she works optimally. She works until the marginal benefits equal her marginal disutility, and then stops. But there is a catch: she works optimally only if she faces a *single* such task. If she has to allocate her time across multiple tasks, or distinct subtasks, I show that she mis-prioritizes by spending too much time on tasks done when she is more rested than on tasks done when she is more tired. Consider a student who has an exam the next day and who studies chapter 1 before switching to chapter 2. When the optimal time for switching comes, she overestimates how much longer she will study later and therefore she keeps studying chapter 1. She studies too much for chapter 1 – done when she is rested – and too little for chapter 2 – done when she is tired. This cannot happen if people constantly switch to the work with the highest marginal return. But since she doesn't realize her mistake, I show that she will complete tasks sequentially if tasks have an element of *time-sensitivity* – any benefit from completing tasks earlier. This suggests that, when multi-tasking, she works too much on early stages of tasks, such as planning or background research, and on time-sensitive tasks which are best done immediately, such as urgent requests from colleagues.

In Section 4, I consider multi-day settings with tasks that are due on some fixed future day. The person plans to work too much at the start of each day and potentially too little at the end. For all-or-nothing tasks, I show that even for an almost unbiased person these repeated unanticipated changes in plans can lead to large welfare losses – up to the point where she does almost all the work necessary to succeed, yet just fails to do so. Consider a person working on an all-or-nothing task, say a student who has to study at least 100 hours to pass an exam. She may start each day planning to complete the task efficiently, yet stop studying earlier than anticipated, planning to drop the exam. This leads to one of two outcomes. Either she passes the exam despite working too little in the early days, having to study harder later on. Or she repeatedly wastes time studying toward an exam that she eventually drops for good. Unless the benefits are increased sufficiently for the student to actually pass the exam, increasing benefits make her worse off, because they lead her to waste even more time across more days for no change in the outcome.

For decreasing returns, I consider the case of multi-tasking between time-sensitive short-term tasks and a single long-term task with fixed deadline. As was the case for multi-tasking in Section 3, due to time-sensitivity of the tasks, people then spend too much time on the short-term tasks at the expense of the long-term task. Unlike the result in Section 3, they do not make up much of the lost time on the long-term task on early days: being tired when working on the long-term task, they underestimate how much time they will fritter away on future short-term tasks, and hence mistakenly plan on making it up in the future without having to work much more on a given day. Thus they fall increasingly behind on the long-term task, working increasingly more each day, highlighting an additional cost of multi-tasking and task-juggling in firms. The general overoptimsm in the examples with decreasing returns is consistent with research showing that people are often overly optimistic in predicting their own task completion. For instance, Buehler, Griffin, and Ross (1994) find that students believe that they will finish their bachelor's thesis earlier than they actually do. They explain this mistake – called the planning fallacy – in terms of students being overly optimistic about how many hours are necessary for the task or how many distractions they will face. Projection bias provides an alternative and complementary explanation, suggesting that people overestimate how much they will work.[3]

In Section 5, I turn to the second mistake whereby projection bias leads people to smooth work too little over time. I fix the total amount of output that has to be produced, but allow productivity to change over time. When productivity is decreasing over time, people delay work too much, and when it is decreasing, they pull it forward too much. Consider a student who has three days to finish her term paper. Let us imagine that because she can receive feedback on her writing, her productivity is 3 pages per hour on the first day, 2 pages per hour on the second day, and only 1 page per hour on the third day. This means that she should work the most on the first day, less on the second, and least on the final day. The projection-biased student realizes that marginal disutility at the end of the first day is higher than at the end of the second day. But, underestimating how much higher it is, she works too much on the first day. More generally, because she underestimates the differences in marginal disutility, she is prone to working too much when her marginal disutility is high for any reason – and hence she effectively overreacts not only to differences in productivity, but also to differences in incentives, opportunity costs, and time preferences.

Since different levels of effort across days means that the plans made at the end of different days can be inconsistent. When productivity changes monotonically, whether it is increasing or decreasing, I show that people work less on a given day than they expected to work at the end of the previous day. This reduction of actual effort compared to past plans moves them closer to optimal behavior when productivity is decreasing, but further from optimal behavior when productivity is increasing.[4]

[3] See Buehler, Griffin, and Peetz (2010) for a review of planning fallacy and of situations where people are overoptimistic about when they will complete a task.

[4] Or rather, it moves them closer or further from how an unbiased person would work on this day if they found themselves in this situation where they have worked suboptimally in the past. Optimal behavior on a single day can only be defined with respect to the effort that will be chosen in the remaining periods.

Thus in our example, the student will work less on the second day than she planned at the end of the first day. The intuition is roughly as follows: the student plans to continue working at the end of day 2 as long as the benefit from doing so exceeds the cost. By working more, she loses an extra hour on day 2, but gains 2 on day 3. Thus she misperceives the gain on day 3 twice as much than the gain on day 2. Since she is more tired at the end of day 1 than at the end of day 2 – given that she is most productive on day 1 – she overestimates the gains more on day 1 than on day 2. This means that at the end of day 1 she plans to work more on day 2 than she will. However, even on day 2 she still overestimates the gains, thus this reduction in effort is still not enough to move her to the optimal effort on day 2. Finally, I note that since exponential discounting is behaviorally equivalent to a person with no discounting and exponentially increasing productivity, a projection-biased person with exponential discounting will exhibit time-inconsistent behavior, delaying too much effort, and working less than anticipated.

Given how important it is whether a person plans more or less work, in Section 6 I study tasks where the marginal disutility is initially *decreasing*. These tasks become easier initially, such as physical exercise and music practice with warm-up, as well as mental tasks that require a high focus, such as programming or writing. Mirroring results in Section 3, I show that such a person *overestimates* the disutility initially and therefore fails to start some worthwhile tasks. I illustrate with an example how this can lead a person to take too many breaks, which causes her either to incur the high disutility from resuming the task or to fail resuming the task against her expectation. The reason is that once she gets going, work is comparatively easy and she underestimates the disutility of resuming the task after a break.

My paper is most closely related to Loewenstein, O'Donoghue, and Rabin (2003) who formalize the model of projection bias and apply it to durable goods consumption, the endowment effect, and habit formation. I focus on effort choices, an economically important domain where projection bias – operating through fatigue, boredom, and exhaustion – will cause repeated fluctuations. Since agents repeatedly reoptimize as they grow tired or rested, the final success of work depends on combining the many decisions made under inconsistent plans.[5] The study of reoptimization closest to the model of instantaneous gratification of Harris and Laibson (2013), including in using ordinary differential equation in continuous-time to approximate the discrete-time optimization of naive agents.[6] This approach may help integrate projection bias into specific economic settings, in particular to personnel economics. For example, Coviello, Ichino, and Persico (2015) and Bray et al. (2016) find empirical evidence of productivity decreases due to multi-tasking. Coviello, Ichino, and Persico (2014) show why workers may engage in intrinsically inefficient multi-tasking due to

[5]Herrnstein and Prelec (1991)'s model of melioration under distributed choices is somewhat related, but differs substantially in the sense that future plans don't matter at all in that model, while they are central to the results in my paper.

[6]Like Harris and Laibson (2013), I assume naiveté: a person is unaware of her bias, which allows for repeated changes in plans. It is beyond this paper to study how a person could be aware of her changing plans without being aware of the underlying reason for the changes.

lobbying by co-workers and superiors. With projection bias, even if multi-tasking is not intrinsically inefficient, such lobbying will lead workers multi-tasking inefficiently. Given the possibly large welfare losses under inconsistent behavior, my results highlight the potential to expand the study of projection bias beyond domains with large swings in taste (Levy (2009); Chaloupka, Levy, and White (2019)) and binding choices (Conlin, O'Donoghue, and Vogelsang (2007); Busse et al. (2015); Buchheim and Kolaska).

2 Projection Bias in Simple Effort Choices

In this section I show how both an unbiased and a biased person choose in a setting where their daily utility U is given by

$$U(E) := B(E) - D(E)$$

where E is the possible number of hours worked. Here, $B(.)$ denotes the daily benefit and $D(.)$ the daily disutility. The person wants to maximize her utility. We usually think of this as a static problem, where the person chooses how much to work and then works that much. This abstracts away from the fact that people work over several hours and thus could decide something else later in the day than what they decided earlier on. Of course, with an unbiased person, in the absence of unanticipated information, the behavior is time-consistent, and modeling the dynamic nature of the problem adds nothing. Since projection-biased people need not have consistent plans, they may want to act differently after, say, 3 hours of work than they thought they would initially. For this reason, this section describes a dynamic setup that boils down to the maximization of U for an unbiased person, and extends it to allow for projection bias in a unique way when B and D are specified.

2.1 A Model of Dynamic Effort Choices Within a Day

The time in the day, $\tau \in [0, \infty)$ is continuous.[7] Each moment, the person either works or does not work, so that $e(\tau) \in \{0, 1\}$. She does not choose to work at a higher or lower intensity.[8] The instantaneous disutility from not working is 0, while the instantaneous disutility from working is $d(s(\tau))$. The latter depends on the current state, $s(\tau)$, which captures tiredness or boredom or anything else that affects how unpleasant effort is at time τ. I assume moreover that $s(\tau)$ depends only on the total amount of effort completed until time τ, which is therefore equal to τ. The

[7] One can also work with $\tau \in [0, \bar{\tau}]$ for finite $\bar{\tau}$.

[8] If I actually add something about intensity later, mention this here in a footnote. Otherwise get rid of this footnote.

interpretation is that the person works continuously without interruptions, and that once she stops working, she doesn't start again.

The final assumption is that people decide each moment whether or not they want to work that moment – they cannot choose at an earlier time whether they will work at a later time. I call such people *self-directed*:

Definition 1. *A person is* self-directed *if she does not make irreversible plans and in each moment work according to the plan she currently perceives as optimal.*

Such self-directed situations are common, certainly at the day-to-day level. Most college students choose their classes, decide whether to attend lectures, and study when they want to. Whenever employees are not monitored around the clock – that is, whenever moral hazard is an issue – they have some lee-way about when and how much they work. This excludes situations where, for exogenous reasons, a person has to make an irreversible decision to work for the next 10 hours, for instance.[9]

So, how does the person actually decide whether or not to work each instant? Given that she is self-directed, the person continues working if she perceives that better than to stop *at that time*. Formally, let $E^*(\tau)$ denote the optimal amount of work a person plans to do at time τ. Then the person continues working at time τ, that is $e^*(\tau) = 1$, if and only if $E^*(\tau) > \tau$ – if she thinks she should work more than she has worked so far. Thus $E^*(\tau)$ solves

$$E^*_\tau = \underset{E:E\geq\tau}{\arg\max}\, B(E) - \int_\tau^E d(s(\tau'))d\tau'$$

where I implicitly assume that benefits in a day depend only on total effort exerted E. The total disutility from effort from working E hours in a day is

$$D(E) := \int_0^E d(s(\tau))d\tau = \int_0^E d(s(E'))dE' = \int_0^E (d \circ s)(E')dE' \tag{1}$$

Thus we have that $d \circ s = D'$, since D is the integral of $d \circ s$. Therefore the maximization problem the person solves becomes:[10]

$$E^*_\tau(\tau) = \underset{E:E\geq\tau}{\arg\max}\, B(E) - (D(E) - D(\tau))$$

[9]In order to see what a person does who is self-directed, I will have to talk about the plans she makes at any time. These plans are effectively the choice she would make at that time if she had to make an irreversible decision. Thus, while I focus on the situation when a person is self-directed, in doing so I will also answer what choices a person would make when not self-directed.

[10]This assumes that the person hasn't already stopped working, in which case she won't restart again (by assumption) and there is nothing to decide.

When there is no uncertainty and the person is unbiased, then $E_{\tau}^{*} = E^{*}$ and we might as well ignore the dynamic nature of the problem. But, as we will now see, it is necessary to state it when people are projection-biased.

2.2 Projection Bias

Loewenstein, O'Donoghue, and Rabin (2003) define projection bias as follows. Let $d(e, s)$ be the instantaneous disutility a person experiences from exerting effort e when in state s. Suppose that a projection-biased person is currently in state s and she predicts how unpleasant effort would be if she were in state s'. Then she misperceives the disutility of exerting effort e' in state s' as lying between the actual disutility $d(e', s')$ and the disutility $d(e', s)$ that she would experience if she exerted the effort right now. The perceived disutility is denoted by $\tilde{d}(e', s'|s)$ and is given by

$$\tilde{d}(e', s'|s) := (1 - \alpha)d(e', s') + \alpha d(e', s) \tag{2}$$

where $\alpha \in [0, 1]$ is the degree of projection bias.[11] When $\alpha = 0$, the person has no projection bias and perceives future disutility correctly; when $\alpha = 1$ she has *full* projection bias and believes that future disutility is equal to current disutility of effort. Whenever there is ambiguity for $\alpha = 1$ – since such a person perceives her disutility as linear – I treat $\alpha = 1$ as the limit of α going to 1.

Thus, projection bias captures two features of how people perceive their future disutility. First, people understand that they will enjoy working less as they grow more tired. They never think that they would want to work even more if only they were more tired. Second, people underestimate how much less they will want to work once they are more tired. This is in line with those studies during which people make choices in two different states, which is necessary to identify whether people have projection bias. For instance Read and Van Leeuwen (1998) show that people choose to receive the more filling snack (a chocolate bar) over the less filling one (a fruit) when they will receive the snack at 4pm – at a time when they will be hungry – rather than at 1pm after lunch. But they also choose to receive the more filling snack more when they are *currently* hungry. Fisher and Rangel (2013) run an experiment where people bid on food. They find that over- and underbidding is symmetric: participants who were satiated bid less for food on a second day where they were hungry than on that day itself, and participants who were hungry bid more for food on the second day where they were satiated than on that day itself.

[11] Specifically, this is what Loewenstein, O'Donoghue, and Rabin (2003) call *simple* projection bias. More general versions of projection bias could allow for α to depend both on the current and the future state which, for instance, would permit people to misperceive more when they are hungry than when they are sated, or vice versa. While there is little evidence on details of the structure of projection bias, Read and Van Leeuwen (1998) require people to choose both in craving and sated states for future craving and sated states. Assuming that people make the correct prediction when they are in the same state as they will be next week, they find that people project their current state whether they are sated or hungry. Moreover, Fisher and Rangel (2013) find that projection bias is symmetric in food choices.

We can now map the definition of projection bias to the current framework. Effort e is either 0 or 1. The disutility of not working, of exerting effort $e = 0$, is 0 no matter what the state is. Therefore the perceived disutility from not working is also 0. Similarly, we have that the perceived disutility of working in a future state s'' when currently in state s', written $\tilde{d}(s''|s')$ is

$$\tilde{d}(s''|s') = (1-\alpha)d(s'') + \alpha d(s') \tag{3}$$

The goal is to rewrite this in terms of daily disutility D and its marginal D', and to replace the potential states s'' and s' by potential amounts of work a person may have completed at different times. In order to do this, let us define the following: $\tilde{d}_{|s'}(s'') := \tilde{d}(s''|s')$ and $\tilde{D}_{|E'}(E) := \int_0^E \tilde{d}_{|s(E')}(s(\tau))d\tau$, where $s(E')$ is the state a person is in after working E' hours. Then $\tilde{d}_{|s'}$ is the *perceived* instantaneous disutility function when the current state is s' and $\tilde{D}_{|E'}$ is the perceived daily disutility of working a given number of hours when the person has already worked E' hours so far that day. These are the instantaneous and daily disutility as the projection-biased person perceives them, and highlights the analogy to the unbiased case. Thus, just as $d \circ s = D'$, we have that $\tilde{d}_{|s'} \circ s = \tilde{D}'_{|E'}$ for all E' such that $s(E') = s'$. Finally, if s'' and s' are possible states, then let E'' and E' denote effort levels such that $s'' = s(E'')$ and $s' = s(E')$ – which must exist, since states by assumption only depend on total effort worked up to the current time.

From equation (3) we obtain the following:

$$\begin{aligned}
\tilde{d}(s''|s') = (1-\alpha)d(s'') + \alpha d(s') &\implies \tilde{d}_{|s'}(s(E'')) = (1-\alpha)d(s(E'')) + \alpha d(s(E')) && (4)\\
&\implies (\tilde{d}_{|s'} \circ s)(E'') = (1-\alpha)(d \circ s)(E'') + \alpha(d \circ s)(E') && (5)\\
&\implies \tilde{D}'_{|E'}(E'') = (1-\alpha)D'(E'') + \alpha D'(E') && (6)
\end{aligned}$$

We can integrate this to obtain

$$\tilde{D}_{E'}(E) = \int_0^E \tilde{D}'_{E'}(E'')dE'' = (1-\alpha)D(E) + \alpha D'(E') \cdot E$$

To make the notation consistent with the notation in Loewenstein, O'Donoghue, and Rabin (2003) and to highlight the difference between the role played by E'' and E' above, I write this as follows:

$$\tilde{D}'(E|s) = (1-\alpha)D'(E) + \alpha D'(s)$$

I call this special case *projecting marginal disutility* and use it throughout the paper.

Observation 1 (Projecting Marginal Disutility)**.** *Suppose the following holds in effort choices during a single period:*

1. *The time in a period is continuous ($\tau \in [0, \infty)$);*

2. *each moment, a person either works or does not work ($e_\tau \in \{0, 1\}$);*

3. *once a person stops working, she doesn't start again, and each moment she is in state $s(\tau)$ that depends only on total work done until time τ*

4. *the instantaneous disutility from working is 0 from not working, $d(s(\tau))$ from working.*

Then the total disutility of working E hours in a row is given by $D(E)$ with $D'(E) = (d \circ s)(E)$ and the perceived disutility $\tilde{D}$ depends on the total amount the person has completed so far that period, denoted by S. Specifically, we have

$$\tilde{D}(E|S) = (1 - \alpha)D(E) + \alpha D'(S) \cdot E \tag{7}$$

where $\alpha \in [0, 1]$ is the degree of projection bias.

Together with the following maximization problem, this completes the single-period setup in a way that allows us to forget about d and s:

$$\tilde{E}^*(S) = \underset{E:E \geq S}{\arg\max}\, B(E) - (\tilde{D}(E|S) - \tilde{D}(S|S))$$

As the next sections will show, $\tilde{E}^*(S)$ is in general not independent of S, so that plans are inconsistent. Before going there, it is important to draw a distinction between the disutility that is projected, and the benefits and opportunity costs.

2.3 Difference Between Utility and Opportunity Costs

Note that a projection-biased person does not project the benefits and opportunity costs. This is not an additional assumption, but follows from the definition of projection bias (and the empirical evidence justifying that definition). Projection bias acts on *utility*, not on choice sets or options available to a person. Projection bias makes a person misperceive the future utility of the options she will have, but it does not make a person misperceive that she will have different options. Economists are of course very familiar with this distinction, for instance from risk aversion. A risk-averse person who believes that a coin is fair perceives the chances of heads and tail as 50% each, just as a risk-neutral person does. But she may give different values to the outcomes of losing \$25,000 or winning \$25,000. The difference between projection bias and risk aversion is of course that risk aversion is about actual preferences, whereas projection bias is about how people perceive their preferences – but it is about how they perceive their preferences, not about how they perceive probabilities or add up money.

Thus a projection-biased student who is at a party right now and therefore has a high current opportunity cost of studying does not then think that her opportunity costs of studying will be high tomorrow at the same time too. What is possible though is that she might perceive those possibilities that make her future opportunity costs as more or less worthwhile depending on whether she feels more or less tired right now. For instance, one alternative to studying might be to go to the gym. It is possible that she might want to go less to the gym the more tired she is from working – not just in comparison to studying, but in comparison to all other remaining activities. In that case, studying would not only affect the perception of future studying, but also of future gym-going, which is bundled into opportunity costs. The reason for ignoring this effect is, first, simplicity; second, the fact that, as long as the effect of studying is substantially larger and more robust than the effect on gym-going, it is a good approximation; and third and finally, the fact that if multiple activities share a common state that changes from any of the activities, that we can model this the way any other complementarities are modeled in economics, and we can unbundle opportunity costs into those tasks that have high complementarities with the activity we are studying, and those that do not.

3 Single-Period Choices

Let us start with single-day decisions where people maximize their daily utility given by $U(E) = B(E) - D(E)$, with the dynamic interpretation described in section 2: people who have worked for S hours so far keep working if they perceive it optimal *at that time*. When the disutility D is convex and the benefits B are linear or concave, a projection-biased person works optimally – despite (in fact, because of) her plans changing. Nonetheless, such a person has overoptimistic beliefs about how much she will work. When she works on multiple tasks each with decreasing returns to effort, this overoptimism makes her spend too much time on tasks done when rested. Finally, I show that when the benefits are all-or-nothing, such that a person receives a known reward if she completes a minimum amount of work, people start overly ambitious tasks. They either end up completing the task despite it not being worthwhile, or they quit the task without receiving any benefits for their effort, which goes wasted.

3.1 Optimal Behavior and Optimistic beliefs with Convex Disutility and Linear Benefits

Consider Anna, a projection-biased student with $\alpha = 0.5$, who has an exam tomorrow. The benefits of every additional hour of studying are equal to 3, and from studying becomes more unpleasant the longer she studies. Specifically, Anna's daily disutility is quadratic in total time studied, thus $D(E) = \frac{E^2}{2}$ and $D'(E) = E$. After having studied for S hours, Anna plans to study until her currently perceived marginal disutility is equal to her marginal benefits (which are constant and equal to 3). I denote the time at which she plans to stop by $\tilde{E}^*(S)$, the total hours she plans to work after having worked for S hours. She perceives her marginal disutility after studying for E hours to lie between her current marginal disutility, $D'(S)$, and her actual marginal disutility after E hours of studying, $D'(E)$:

$$\underbrace{\tilde{D}'(E|S)}_{\text{Perceived } D'} = (1-\alpha)\overbrace{D'(E)}^{\text{Actual } D'} + \alpha \underbrace{D'(S)}_{\text{Current } D'} = \frac{1}{2}(D'(E) + D'(S))$$

At the start of the day, Anna hasn't studied at all and $S = 0$. So she thinks that her marginal disutility after E hours of studying will be $\tilde{D}'(E|0) = \frac{1}{2}D'(E)$. She plans to work for $\tilde{E}^*(0)$ hours, with $\tilde{D}'(\tilde{E}^*(0)|0) = 3 \iff \frac{1}{2}\tilde{E}^*(0) = 3 \iff \tilde{E}^*(0) = 6$. Anna plans to study for 6 hours and thus starts studying. After 2 hours of studying, the current marginal disutility is $D'(2) = 2$. Anna now plans to study for $\tilde{E}^*(2)$ hours in total, with $\tilde{D}'(\tilde{E}^*(2)|2) = 3$ – the first order condition as she perceives it now. This leads to $\tilde{E}^*(2) = 4$ hours. Finally, once she has completed 3 hours of studying, the current marginal disutility is $D'(3) = 3$, so that $\tilde{E}^* = 3$ and Anna stops studying.

The same logic applies when the returns to effort are decreasing rather than constant, so this example essentially proves proposition 1. (All proofs can be found in the appendix.)

Proposition 1. *$D(.)$ is strictly convex and $B(.)$ is linear or concave, $\alpha < 1$. Then a projection-biased person who is self-directed works optimally. Moreover, letting $\tilde{E}^*(S)$ be the optimal amount of work as perceived by the person after having worked for S hours and E^* the optimal amount, we have that $\tilde{E}^*(S) > E^*$ $\forall S < E^*$.*

Proposition 1 also highlights that Anna constantly overestimates how much she will work. Why? By assumption, the marginal disutility of effort increases, so that Anna – who projects her current marginal disutility – underestimates how high marginal disutility will be later that day, and therefore overestimates for long she will study.

Proposition 1 relies on the person being self-directed. If Anna had to make an irreversible (or hard-to-reverse) choice, then she would choose to work too much. This is not likely in the case of studying, but may be the case if Anna is grading exams for a course or working on a common project with a friend. In such situations, due to being overoptimistic, Anna will work too much, since she underestimates how unpleasant work later in the day will be.

This strongly limits the scope of the result: while behavior is optimal when the disutility is convex and benefits are linear or concave, the beliefs over future work are overoptimistic. As long as overoptimistic beliefs don't affect other decisions, everything is well. However, as soon as some current decisions rely on predictions of future effort, mistakes will be made, such as when a person has to decide whether to do a time-sensitive task right now. I highlight this major caveat to the optimality result in proposition 2. When a task consists of many small subtasks, each with concave benefits, a projection-biased person no longer exerts optimal effort, because she spends too much time on some subtasks at the expense of others. Then, I consider tasks with all-or-nothing benefits: benefits are received only if the person completes a minimum number of hours.

3.2 Multi-Tasking with Concave Benefits

Let us now revisit the situation with convex disutility and decreasing returns to effort, but with a twist: the person now divides her time between two tasks, each of which has decreasing returns to effort. One of the tasks is more *time-sensitive* than the other task:

Definition 2. *Task A is more* time-sensitive *than task B if the benefits from task B are depreciating faster than those of task A, so that (conditional on doing both tasks) task B should be done first. When there are only two tasks, I call the more time-sensitive task simply the* time-sensitive task *and the less time-sensitive task the* flexible task*.*

A task with an early deadline is more time-sensitive than a task with a late deadline or no deadline. So is a task where there are very small benefits from early completion – such as impressing one's boss or colleagues by completing a task quickly. To illustrate, suppose that Elaine has two problem sets due the same day, one in economics due at 3pm and one in mathematics due at 8pm. Given these deadlines, she starts working on the economics problem set first. For simplicity, assume that the benefits for each problem set are the same and given by $B(.)$, which has decreasing marginal returns. After working on the first problem set for S hours, she plans to spend $E(S)$ hours on each assignment. She thus stops working on the economics assignment when she thinks that she thinks that she has done half the work. Let's say that this happens after 5 hours, at which point she thinks that she will do another 5 hours on the mathematics assignment. She is of course wrong, and overestimates how long she will keep working. Thus she may stop working after only 3 hours on the mathematics assignment. We know from proposition 1 that this choice is optimal *conditional* on her having spent 5 hours on the economics assignment – so the mistake she makes is to spend too much time on the economics assignment, because she is overly optimistic at that time. As proposition 2 shows, while she works less on the second assignment than she should have, she works more in total than would have been optimal.

Proposition 2. *There are two tasks: a time-sensitive one with stictly concave benefits $B_S(.)$, and a flexible one with strictly concave benefits $B_F(.)$. Let $\tilde{E}_S$ and $\tilde{E}_F$ be the actual effort spent on the time-sensitive and flexible task respectively, and E_F^* and E_S^* be the optimal effort levels. Then $B'(\tilde{E}_F) > B'(E_F^*) = B'(E_S^*) > B'(\tilde{E}_S)$ and $\tilde{E}_F + \tilde{E}_S > E_F^* + E_S^*$.*

The proposition states that, optimally, Elaine should have worked less in total than she did, and she should have spent more time on the later task, and less on the earlier task. She works too much because, by the time she should stop – say after 7 hours – she has only spent 2 hours on the mathematics assignment, due to spending too much time on the economics assignment. Therefore her marginal benefit from working on the mathematics assignment is higher than it would be had she worked optimally, and therefore she continues (correctly, given that she cannot undo her earlier mistake) to work for longer to receive some of these high marginal benefits.

A projection-biased person makes the same mistake when working on a single task consisting of two or more subtasks, as long as each subtask is best done in one continuous session. If the subtasks have a natural sequence, so that one subtask makes the subsequent subtask easier, then Elaine will work too much on the earlier stages than on the later stages. For instance, suppose that Elaine plans to read both the lecture notes and to finish a problem set for the same class today. If she believes that the problem set will be easier after reading the lecture notes, then she reads the lecture notes first and consequently spends too much time on them.

In proposition 2, I assume that the person completes the first task fully before switching to the second task. If instead the person constantly switches to the task with the highest current marginal benefit, then we are back to the result of proposition 1. I already mentioned one situation where this is likely not the case: when there is a natural order in which a person should do the tasks. A more general reason why this is unlikely to happen is switching costs. Even very minor switching costs will keep Elaine from switching, since she doesn't realize that her decision would be beneficially affected by doing so. Moreover, the problem may often be substantially worse than I described it, since most tasks consist of multiple subtasks. A problem set consists of multiple problems, and thus Elaine will spend too much time on the early questions at the expense of later questions, even if she did switch between the mathematics and economics problem set. There is one very situation where Elaine would switch more often: If Elaine is uncertain over how long she will take for the individual tasks or subtasks, and she learns from working on each subtask, then she will quite naturally switch between them in order to identify those tasks that will take her a long time and those that won't.[12] Thus, in this particular instance, Elaine may be better off when she is more uncertain about the benefits of each subtask, because this will lead her to switch more often.

3.3 Fixed-Hours Tasks

I now study the choice of a self-directed projection-biased person who can work on a single-day *all-or-nothing* task:[13]

Definition 3. *A single-day* all-or-nothing *task is a task that has benefits B only if the person*

[12] More formally, what Elaine is uncertain about is how quickly the marginal benefits decrease from each subtask.

[13] All-or-nothing tasks include tasks where a person makes a hard-to-reverse choice or commitment to another person to complete a certain task – thus even tasks that may not naturally be all-or-nothing (such as studying) may become so if an outsider sets incentives in that way.

completes at least E hours by a known deadline.

Each instant, the person chooses whether to start or continue the task. She does so if and only if she *currently* thinks that completing the task is better than quitting the task. Suppose that Alice, a projection-biased high-school student with $\alpha = 0.5$, has a deadline to finish a college application tonight, which will take her 6 hours. Let's say that $D(6) = 18$ and $B = 12$, so that Alice should not complete the application. For an unbiased person, the decision is clearcut: since the disutility exceeds the benefits, the task is not worth doing. Whether Alice starts the application depends also on how unpleasant the task is at the start.

Does she start the application and, if so, does she finish it? She starts if the perceived disutility $\tilde{D}(6|0)$ is less than B. But $\tilde{D}(6|0) = (1-\alpha)D(6) + \alpha D'(0) \cdot 6 = 9 + \alpha D'(0) \cdot 6$. If $D(E) = \frac{E^2}{2}$, so that $D'(E) = E$, then $\tilde{D}(6|0) = 9 < 12 = B$ and Alice starts the application. After one hour, we have that the perceived disutility from completing the application is $\tilde{D}(6|1) - \tilde{D}(1|1) = \frac{1}{2}(D(6) - D(1)) + \frac{1}{2}D'(1) \cdot 5 = 11.5 < 12 = B$. Thus Alice continues studying. Now imagine what happened if Alice worked for another hour – which, as we will see, does not happen. Then the perceived disutility of completing the application would be $\tilde{D}(6|2) - \tilde{D}(2|2) = 13 > 12 = B$, and so she would not want to continue working. It is clear that Alice will have stopped working before this point. This shows that, as she keeps working, Alice's perception of how unpleasant it is to complete the application increases – something that cannot happen for an unbiased person. As current effort becomes more unpleasant, the final 4 hours of work seem more unpleasant than they did at the start. Because the task now seems harder to complete than it did initially, Alice may decide to quit. Proposition 3 states formally when this happens.

Proposition 3. *A self-directed person with strictly convex disutility D works on an all-or-nothing task that requires effort E to complete and has benefit B if completed. Let $\tilde{E}$ be the actual effort exerted and $U(e) = \mathbb{1}(e = E) \cdot B - D(e)$ the utility of working e hours. Then there exists a unique $E_H \geq 0$ such that the following statements hold:*

1. $\forall E$, $\exists B$ *s.t.* $U(E) < 0$ *and* $\tilde{E} > 0$
2. $\forall E < E_H$ *if* $\tilde{E} > 0$ *then* $\tilde{E} = E$.
3. $\forall E > E_H$, $\exists B$ *s.t.* $0 < \tilde{E} < E$.

The first point of proposition 3 states that for any task, we can find a payment such that a person starts the task even though the task isn't worth doing. The proposition also states that there is a threshold E_H such that if a task requires less work than E_H hours, then Alice finishes the task if she starts it, even if the task isn't worth doing. If on the other hand the task requires more than E_H hours of work, it is always possible to find a benefit such that Alice starts the task, yet she doesn't complete it. In fact, it is possible to show that when $D'(0) = 0$, then $E_H = 0$, so that starting and stopping can happen for all tasks, no matter how small.

Proposition 3 applies more widely to tasks with sufficiently convex benefits, although the mistake is the most obvious in for all-or-nothing tasks. Take a task that has increasing returns to effort, so that the benefits $B(\cdot)$ are convex, and which allows for a maximum effort of E. Let $D'(0) > B'(0)$ and $(1-\alpha)D''(\cdot) < B''(\cdot)$. Then for both an unbiased and a projection-biased person with projection bias α, it is either optimal to work 0 hours or to work E hours. Yet, even though the person at every moment perceives not doing the task at all, or doing the task fully as the only options, she may end up working a little before giving up. Unlike in all-or-nothing tasks, there are some benefits from the work the person puts in. Since we may often not know that $D(\cdot)$ and thus not know whether the person should either put no work in or do all the work, in these situations it is harder to infer whether the behavior was a mistake or not. One type of situations where benefits are convex is when success is discrete – such as receiving an A in an exam, getting a job or promotion – and the probability of success is S-shaped in the amount of effort exerted.

The behavior described here – that people start a task that they don't finish – is similar to people starting but not finishing multi-stage projects as studied in O'Donoghue and Rabin (2008) driven by naive present bias. The important difference is that in O'Donoghue and Rabin (2008) people procrastinate: they repeatedly fail to do a task today, because they think that they will do the task tomorrow. In the case of projection bias, people quit, fully aware that they will *never* complete the task, since the deadline is the same day. Thus there is no scope for procrastination in this setting.[14] Another difference is that a projection-biased student who quits a task is better off quitting – since she underestimates the disutility of completing the task even at the time of quitting – whereas a present-biased person would benefit from completing the task.[15] Thus, while a naive procrastinator would benefit from committing to complete the task, a projector would be hurt by it.

4 Multi-Day Tasks and Multiple Deviations

In single-day tasks, a person with increasing marginal disutility is always overly optimistic about how much she will work. In multi-day tasks, she is overly optimistic at the beginning of each day, but if she works long enough, she becomes overly pessimistic: her marginal disutility is higher than it will be in the future, and she thinks that she therefore underestimates how much she will work

[14] It is still possible that a person with naive (but not sophisticated) present bias starts a task that they don't complete if they have present bias at the hourly time frame, but this is substantially less likely than procrastination, since procrastination entails delaying benefits, whereas dropping a task entails never receiving them. Moreover, if present bias is over really short time intervals (say 10 minutes), then it is unlikely to be a plausible explanation.

[15] Here I apply the welfare criterion based on a person's long-run perspective, as in O'Donoghue and Rabin (1999). Even if one does not apply that criterion, the projection-biased person is always better off quitting in this setup.

on future days. She may therefore repeatedly change her mind about whether a task is worth doing, fluctuating between perceiving it worthwhile when work the marginal disutility is low and perceiving it not worthwhile when her marginal disutility is high. In this section I study the how these fluctuations affect effort choices, as well as the welfare implications thereof. Throughout the section the marginal disutility is strictly increasing during a day, and given by $D(\cdot)$.

4.1 Multi-Day All-or-Nothing Task

Consider Beth, a student who is working on an all-or-nothing task with a deadline in T days. She has an economics exam in 100 days and knows that she will receive a B in her final if she does nothing but attend the required lectures. Getting an A on the final has a value of $1,250$ to her. If she studies 5 hours a day on average, Beth is sure to receive an A.

The daily disutility is quadratic: $D(E) = \frac{E^2}{2}$ and $D'(E) = E$. First, note that Beth at every moment either plans to complete the task efficiently, or to not do the task at all. After all, at any given moment she plans to do what an unbiased person would do whose actual disutility was given by $\tilde{D}(.|S)$. On the first day, Beth therefore studies so long as she perceives it worthwhile to study 5 hours every day. The disutility of studying 5 hours per day is $100 \cdot D(5) = 1250$, so an unbiased student would be indifferent between studying and not studying. But Beth is projection-biased, with $\alpha = 0.5$. At the start of the first day she underestimates the disutility of the task and starts studying. After 2.5 hours of studying, her marginal disutility is $D'(2.5) \cdot 5 = 2.5 \cdot 5 = 12.5 = D(5)$, and she perceives the disutility of working 5 hours on every future day correctly: $\tilde{D}(5|2.5) = (1 - \alpha)D(5) + \alpha D'(2.5) \cdot 5 = D(5)$. She therefore perceives the remaining disutility of studying 5 hours every day almost correctly: she still slightly underestimates it because she underestimates the disutility of the 2.5 hours of work she has to complete on the first day. Thus, she keeps studying a little, and as she does so, she overestimates the disutility of studying 5 hours on future days and therefore soon stops working.[16] At the time she stops studying, she perceives the task no longer as worth doing and believes, mistakenly, that she won't resume it the next day. At the beginning of the next day, the same pattern repeats: she starts studying when effort is not very unpleasant is, planning to get an A; and then she stops once effort becomes sufficiently unpleasant.

When does this happen that Beth starts studying with the intention of studying 5 hours, yet she stops studying before she has done 5 hours? If average daily benefits are strictly lower than $\tilde{D}(5|0) = 6.25$, Beth will not start studying, since she doesn't perceive it worthwhile even at the beginning of the day. Similarly, it can be shown that she will work for a full 5 hours if the benefits are strictly larger than $99 \cdot \tilde{D}(5|5) = 99 \cdot 18.75$ – she perceives the remaining 99 days of

[16]More concretely, she certainly will stop working when she perceives the disutility of working 5 hours on all future days as equal to the benefits of getting an A, that is once $\tilde{D}(5|S) = \frac{1250}{99}$, which we can solve for S and find that $S \approx 2.56$. In this particular case, she thus won't work more than 2.56 hours on the first day.

work as worthwhile, even at the end of the first day.[17] For daily benefits in the range between $(6.25, \frac{99}{100}18.75)$, Beth will start studying on day 1, yet stop before having done 5 hours.

Every day, Beth thus either doesn't study at all, studies inefficiently given how much work still remains to be done, or studies efficiently. It is not difficult to see that if Beth doesn't study at all on day t, than she won't study on day $t+1$ or any later day either, and therefore not get an A. Similarly, if she studies efficiently on day t, then she will study efficiently on all future days and thus get an A. For instance, if after 50 days, Beth had only completed 50 hours of studying, she would have to study 9 hours per day on the remaining days, and she wouldn't start studying any longer. Alternatively, if after 75 days Beth had completed 300 hours of studying, she would have to work 8 hours a day for the remaining 25 days to receive the full benefits worth 1250. She would work 8 hours a day, since she would perceive this as worthwhile even after 8 hours of work: $\tilde{D}(8|8) = 16 + 32 = 48 < 50 = \frac{1250}{25}$. Whether or not these situations also can happen for some initial benefit is answered by proposition 4.

The proposition formally states that for any average daily effort required, each of these two outcomes – wasting effort on a task that won't be completed and working inefficiently for a while on a task that is completed – will happen for some average daily benefit, provided that the number of days is sufficiently large. Thus, in our example, this means that if Beth has to study on average 5 hours per day to receive some benefit $T \cdot b$, then we can pick $b = b_L$ such that Beth will fail to achieve the goal, yet waste time studying, and we can pick another benefit $b = b_H > b_L$ such that she will study 5 hours on average and receive the A, but she will work less initially and more at the end. It shouldn't be surprising that T has to be large, since the result is clearly wrong for $T = 1$ given what we know from the single-day settings. There we had, for instance, the result that people finish all tasks that they start if the task requires effort E less than some E_H (proposition 3).

Definition 4 (Multi-Day Task)**.** *The triplet* (E_0, B_0, T) *denotes the following* multi-day task*: the task has to be completed in* T *days, requires* $E_0 \cdot T$ *hours of work to be completed and pays* $B_0 \cdot T$ *if completed by the end of day* T*.*

Definition 5 (Partial Work)**.** *Take a multi-day task* (E_0, B_0, T)*, let* $e_t(E_0, B_0, T)$ *be the amount of work the person actually exerts on day t, and let* $E_t := T \cdot E_0 - \sum_0^{t-1} e_i$ *be the amount of work that still remains to be done at the start of day t in order to complete the task. Then a person* works partially *on day t if* $e_t > 0$ *and* $e_t < \frac{E_t}{T-t+1}$*, that is she does some work, but stops working earlier than is efficient if she plans to complete the task.*

Next I define the number of days for which a person doesn't work at all, and the number of days for which a person works efficiently, or fully (given the amount of effort remaining).

[17] The condition that the disutility of work on future days is perceived worthwhile is necessary, but may appear not sufficient. In this case, it is sufficient because one can show that the perceived disutility of completing the task is strictly increasing over the course of the first day, so that it is enough to know the perceived disutility of completing the task as perceived at the end of the first day, after 5 hours of work – which is given by the $99 \cdot \tilde{D}(5|5)$.

Definition 6. *Let $g_0(E_0, B_0, T)$ be the number of days for which $e_t = 0$, and let $g_F(E_0, B_0, T)$ be the number of days for which $e_t = \frac{E_t}{T-t+1}$. Let $\tau_i(E_0, B_0, T) = \frac{g_i(E_0,B_0,T)}{T}$ for $i \in \{0, F\}$.*

With these definitions out of the way, I can state the main proposition of this section:

Proposition 4. *The disutility of effort is strictly convex with $D''(E) > d$ for all E, for some $d > 0$ and $D'(E) \to \infty$ as $E \to \infty$. Consider a task (E_0, B_0, T) with $E_0 > 0$ fixed. Then there exist $B_H(E_0) > B_C(E_0) > B_L(E_0) > 0$ with $B_H(E_0) > D(E_0) > B_L(E_0)$ such that*

- *if $B_0 > B_H$, then the task is completed efficiently.*
- *if $B_H > B_0 > B_C$, then $\lim_{T\to\infty} \tau_F(B_0, T) = \tau_F(B_0) \in (0, 1)$ and the task is completed inefficiently.*
- *if $B_C > B_0 > B_L$, then $\lim_{T\to\infty} \tau_0(B_0, T) = \tau_0(B_0) \in (0, 1)$ and the task is not completed.*
- *if $B_L > B_0$, then no effort is spent on the task.*

where $\tau_0(B_0)$ is continuous and decreasing in B_0 and $\tau_F(B_0)$ is continuous and increasing in B_0. Moreover, letting $\bar{U}(B_0, T) = \mathbb{1}(B_0 > B_C)B_0 - \frac{\sum_{t=1}^{T} D(e_t(B_0,T))}{T}$ be the average daily utility from task (E_0, B_0, T), we have that $\bar{U}(B_0) := \lim_{T\to\infty} \bar{U}(B_0, T)$ is well-defined for $B_0 \in [0, B_C) \cup (B_C, \infty)$, is strictly decreasing on (B_L, B_C) and strictly increasing on (B_C, B_H) with $\lim_{B\to B_C^-} \bar{U}(B) \leq -D(E)$.

What does the proposition mean? Notice first that the *average* daily effort and *average* daily benefit are fixed – rather than total effort and benefit – but the number of days the task requires potentially has to be very large. For instance, a problem set may be due in 5 days, yet require an average of 2 hours of work per day, while the final exam may be in 2 months and also require an average of 2 hours of work per day. The proposition then states that if we fix the average effort for a task, there exist three thresholds $B_H > B_C > B_L > 0$ such that if the actual average benefit of the task is low enough (strictly less than B_L), then Beth never starts the task – intuitively this is because the payment is too low for her to want to start the task on the first day. If the average benefit is large enough (strictly larger than B_H) then Beth will complete the task efficiently, because she perceives the task worth doing at all times.

If the payment B lies in (B_L, B_C) – which is a non-empty interval for every $\alpha > 0$ and every $E_0 > 0$ – and if the task requires sufficiently many days (which depends both on B and on E_0), then Beth spends some days working inefficiently until some day T_0 from which point onward she never does any further studying. The day T_0 is moreover such that $\frac{T_0}{T} \approx \tau_0(E_0, B)$, which means that if T is sufficiently large, and if $\tau_0(E_0, B) = 0.3$ say, then Beth always spends close to the first 30% of days wasting pointless effort before she stops working for good. If the payment B lies in (B_C, B_H), the result is similar, except that Beth spends the first 30% of days working inefficiently before working efficiently on the task and finishing it.

The proposition also states that $\tau_0(E_0, B)$ is continuous and decreasing in B. Since τ_0 is the fraction of days a person spends not working at all, it is clear that it goes from 1 to 0. This means that there is some B such that Beth spends 10% of days not working (the final 10% of days) or 1% if the benefits are larger, or 0.1 if the benefits are even larger. Thus increasing the benefits initially doesn't lead to completion of the task, but simply causes Beth to waste more effort for more days on a task she fails to complete. The second part of the proposition states that this in fact can lead Beth to almost complete the task, yet just fall short, which of course means that she has occurred almost all of the disutility of doing the task – on average $D(E_0)$ per day – yet receives no benefits. Thus the repeated fluctuations may lead her to incur this welfare loss. In the example given previously where Beth needs to study 5 hours per day on average, this states that Beth may incur welfare losses close to $D(5) = 12.5$ per day on average.

Why does the result rely on T being large enough? I prove the result for a continuous-time equivalent of proposition 4, where the actual effort levels, as well as τ_0 and τ_F are continuous, which makes it much easier to prove the results. In a setting with T days, τ_0 clearly need not be continuous in E_0 and B: if for a small increase in B Beth wastes effort for one more day, then τ_0 jumps discontinuously since it is the fraction of two integers. As T becomes large, it is possible to approximate the discrete-time solution with the continuous-time one, which proves the result.

4.2 Multi-Day Multi-tasking

As we saw previously, a projection-biased person works optimally on a single task with concave benefits, but when she multi-tasks, she works too much on time-sensitive tasks at the expense of more flexible tasks. I now consider multi-tasking over multiple days. Specifically, I consider what happens when Carla, a projection-biased student with projection bias 0.5, has an exam in T days, and has to decide how much time to spend on various short-term tasks each day, such as administrative tasks or attending lectures. As in one-day situations, Carla is overoptimistic about how much she will work each day. This leads her to do too many of the time-sensitive tasks during the day. Unlike in one-day situations, Carla doesn't work as hard at the end of the day to catch up, because she underestimates how many time-sensitive tasks she will do on future days. In short, she thinks that in the future, unlike today, she will focus more on studying for the exam than she did today.

Suppose that Carla has an economics exam in 2 days. She receives benefits of 6 for each of the first 8 hours of studying until then, and 3 for every hour thereafter. Each day, she can also attend 2 hours of lectures for a mathematics class, each hour of which gives her benefits of 4. Carla's disutility is given by $D(E) = \frac{E^2}{2}$.[18] What will Carla do? As long as she has worked less than 2

[18] As before, effort on economics studying or attending lectures has the same effect on her disutility, which is a simplification. As long as the disutility for studying economics depends on some kind of 'tiredness' that increases with the amount of time spent on doing mathematics, the results are qualitatively the same.

hours, Carla thinks that the marginal disutility after 6 hours of work (4 from studying, and 2 from attending the lecture) is less than $\tilde{D}'(6|2) = \frac{1}{2}(D'(6) + D'(2)) = 4$. Since the benefits from the lecture are equal to 4, she therefore plans to attend the lecture. Following the lectures, she plans to study for 4 hours, but after 2 hours of studying, she realizes that the marginal benefit of attending the lecture tomorrow is less than the marginal disutility. She therefore no longer plans to attend tomorrow's lecture, and thus plans to do the 8 hours of studying by working 5 hours each day and studies 3 hours the first day. Yet, she starts the next day refreshed and attends the lecture, only to realized after 1.5 hours that it isn't worth staying. After 4.5 hours of additional studying, she gives up, having studied only 7.5 hours in total, and having worked 1 hour more on the second day than on the first.

As proposition 5 shows, if a person first works on short-term tasks before working on long-term tasks, then the person works too much on the short-term tasks at the expense of the long-term task, and works more and more each day. On earlier days, she stops work early because she underestimates how much time she will fritter away on future time-sensitive tasks, and therefore has to work longer to achieve the gains from the long-term task.

Proposition 5. *A person works on one long-term task over T days with total benefits $B_L(\boldsymbol{l}) = T \cdot B_l\left(\frac{\sum_{t=1}^{T} l_t}{T}\right)$, where $B_l(\cdot)$ represents the average benefits for average daily effort. Each day they face a short-term task with benefits $B_f(f_t)$. Both B_l and B_f are strictly concave. Let $\tilde{\boldsymbol{f}}$ and $\tilde{\boldsymbol{l}}$ be the vector of amounts of effort spent on the short-term and long-term tasks by a projection-biased person, and f^* and l^* the optimal daily amounts – which are single-valued since optimal effort is constant over time. Let $\tilde{f}^*$ and $\tilde{l}^*$ be the amounts exerted in the single-day setting by the biased person described in proposition 2 with one-day benefits from the (no longer) long-term task $B_l(\cdot)$.*

Case 1: when the person works first on the long-term task, then the behavior is equivalent to the single-day setting: $\tilde{f}_t^* = \tilde{f}^*$ and $\tilde{l}_t^* = \tilde{l}^*$.

Case 2: when the person works on the short-term task first, then:

1. *$\tilde{f}_1^* = \tilde{f}^*$: the amount worked on the short-term task is the same on day 1 as in the one-day problem*
2. *$\tilde{l}_1^* < \tilde{l}^*$: the amount worked on the long-term task is strictly less on day 1 than in the single-day setting.*
3. *Total daily effort, $\tilde{f}_t^* + \tilde{l}_t^*$, strictly increases over time*
4. *Daily effort spent on the short-term task, $\tilde{f}_t^*$, strictly decreases over time*
5. *Daily effort spent on the long-term task, $\tilde{l}_t^*$, strictly increases over time*
6. *Average daily effort spent on the short-term tasks, is strictly lower than effort spent on the first task in the single-day setting past the first day: $\frac{1}{t}\sum_{t=1}^{t} \tilde{f}_i^* < \tilde{f}^* \forall t > 1$*

7. *Average daily effort spent until day t on the long-term task is strictly lower than optimal for all t: $\sum_{i=1}^{t} \tilde{l}_t^* < t \cdot l^* \forall t$.*

Note that it is *not* true that the person spends less time on the long-term task on average than in the single-day setting, although this can happen.

In the example, Carla attends the lectures first because I assumed the lectures are early in the day. This need of course not always be the case, although there is one natural setting where Carla would first work on the short-term task before working on the long-term task. Suppose that Carla is uncertain both about the marginal benefits of the short-term task and the long-term task, and she learns about those benefits while working on the tasks. If a task turns out to be more beneficial than she expected, she will want to work for longer. If the task she learns about is a short-term task, then she should work on the short-term task first, since she will be able to smooth the shock over all the remaining days, by working less on the long-term task today and make up for it on future days. For instance, suppose that Carla first works on the problem set and learns that she will work 1 hour more than expected. Then she can work one hour more on the problem set, yet only work one tenth of an hour more in total the first day by spreading the shock across the remaining days. If on the other hand she first studies for the exam, then once she finds out that she will work one additional hour, she cannot undo her studying, and so can no longer smooth work across days. Thus, in the case of uncertainty it will be quite natural for Carla to work first on the short-term task — and thus to end up spending too much time on short-term tasks.

5 Careless Timing: Misallocation of Effort

In the previous section I showed that, even though they always plan on completing the task efficiently or not at all, projection-biased people may complete tasks inefficiently. This is because their plans may fluctuate between completing a task and dropping it. In this section I show that projection-biased people make plans that allocate effort inefficiently, even if their total effort is fixed and they never decide to drop the task. The reason is that projection-biased people underestimate the difference in marginal disutility at different times and therefore are too willing to work more on days when they receive larger marginal benefits for their work or on days when their productivity is higher.

5.1 Misallocation due to Benefit Incentives

A person on day 0 plans how much to work between days 1 and T. She has worked for S hours on day 0, so that the instantaneous disutility from working is $D'(S)$. She plans to work $\tilde{\boldsymbol{e}}(S) = (\tilde{e}_1(S), ..., \tilde{e}_T(S))$ where $\tilde{e}_t(S)$ is the day-t effort. These plans maximize her current perceived utility:

$$\tilde{U}(\tilde{\boldsymbol{e}}|S) := B(\tilde{\boldsymbol{e}}) - \sum_{t=1}^{T} \tilde{D}(\tilde{e}_t|S) = B(\tilde{\boldsymbol{e}}) - (1-\alpha) \sum_{t=1}^{T} D(\tilde{e}_t) - \alpha D'(S) \cdot \tilde{E} \tag{8}$$

where $B(\tilde{\boldsymbol{e}})$ is the benefit from working and $\tilde{E} := \sum_{t=1}^{T} \tilde{e}_t$ is total effort across all days. I will use the following lemma:

Lemma 1. *Let $U_a(\boldsymbol{e}) = X(\boldsymbol{e}) + a \cdot Y(\boldsymbol{e})$, with X and Y continuous (real-valued) functions of the vector $\boldsymbol{e}$, and $a \in \mathbb{R}$ a fixed parameter. Let $\boldsymbol{e}(a) \in \arg\max_{e \in \mathcal{E}} U_a(\boldsymbol{e})$ for some compact set $\mathcal{E}$. If $a_H > a_L \geq 0$, then $X(\boldsymbol{e}(a_H)) \leq X(\boldsymbol{e}(a_L))$ and $Y(\boldsymbol{e}(a_H)) \geq Y(\boldsymbol{e}(a_L))$.*

Lemma 1 says that if a person maximizes a sum of two utilities then the person who puts more weight on the second dimension chooses a bundle with higher utility in that dimension.

Now suppose a person works on a given task requiring a fixed amount of effort $E := \sum_{t=1}^{T} e_t$. We can rewrite total utility from equation (8) as follows

$$\tilde{U}(\tilde{\boldsymbol{e}}|S) = B(\tilde{\boldsymbol{e}}) - \sum_{t=1}^{T} D(\tilde{e}_t) + \alpha \left(\mathbb{E}_0 \left(\sum_{t=1}^{T} D(\tilde{e}_t) \right) - D'(S) \cdot E \right) \tag{9}$$

We can apply lemma 1 to see that a more biased person chooses effort such that $\mathbb{E}_0 \left(\sum_{t=1}^{T} D(\tilde{e}_t) \right) - D'(S) \cdot E$ increases with α. Thus total disutility increases or total effort E decreases or both. When total required effort $E := \sum_{t=1}^{T} e_t$ is fixed, it must be the case that total disutility increases. Of course, a projection-biased person only increases the disutility if this also increases the benefits, i.e. $B(\boldsymbol{e}') > B(\boldsymbol{e})$ where $\boldsymbol{e}'$ is the new effort allocation and $\boldsymbol{e}$ the original. She thus overreacts to benefits and (non-disutility based) opportunity costs, underestimating how much this will cost her, as shown in the next proposition.

Proposition 6. *Suppose that the person has to complete total effort E by day T and receives benefits $B(\boldsymbol{e})$ that depend on when work gets done. Then we have that $\tilde{\boldsymbol{e}}^*(S) = \tilde{\boldsymbol{e}}^*$, so that planned effort does not depend on S. Moreover, $\tilde{\boldsymbol{e}}$ is the same as that of an unbiased person with actual disutility $(1-\alpha)D$ or, equivalently, with net benefits $\frac{B}{1-\alpha}$.*

One important special case of benefits depending on when work is done comes from exogenous changes in the opportunity cost of time. Let us consider what kinds of mistake this can lead to. Doris, a projection-biased student, has to decide how to split 10 hours of studying across two days. Her disutility of effort is convex, so that it becomes more unpleasant to keep studying the longer she has studied. A good friend is visiting town tomorrow, so that Doris has higher opportunity costs of time tomorrow than today. She therefore should work more today than tomorrow, say 7 hours today and 3 hours tomorrow. But Doris underestimates how much more unpleasant it will be to work an additional hour tomorrow and thus works even more today than she should, say 8 hours.[19] In section 6, I show that when the marginal disutility is decreasing, then this underestimation leads projection-biased people to take too many breaks.

5.2 Productivity and Time Discounting

Let us now move to a setting where people have different productivities on different days. This has two implications. First, like the case of benefits, this causes the agent to smooth too little. Unlike the case of benefits this leads to time-inconsistent behavior: for both strictly increasing and strictly decreasing productivity, at the end of one day, the agent expects to work more the next day than they actually will. I then show that a setting with exponential time discounting with time discount factor δ with constant productivity has identical behavioral implications as having productivity increase by a factor $1/\delta$ each period. Therefore a projection-biased person with exponential discounting displays time-inconsistency.

Let us start with a warm-up example. Doris has to complete an assignment by tomorrow night that requires E hours. Her productivity p on day 1 is higher than on day 2, because a friend has offered to give feedback at the end of day 1. Thus every hour of work exerted on day 1 leads to p hours worth of output, so she has to choose e_1 and e_2 s.t. $2 \cdot e_1 + e_2 = E$.

On the first day after having worked for S hours, she plans to stop after completing $e_1(S)$ hours today, given by

$$\begin{aligned}
& \frac{\tilde{D}'(e_1(S)|S)}{p} = \tilde{D}'(e_2(S)|S) \\
\iff & \frac{\tilde{D}'(e_1(S)|S)}{p} - \tilde{D}'(e_2(S)|S) = 0 \\
\iff & (1-\alpha)\frac{1}{p} \cdot D'(e_1(S)) + \alpha\frac{1}{p} \cdot D'(S) - (1-\alpha)D'(e_2(S)) + \alpha D'(S) = 0 \\
\iff & \frac{1}{p} \cdot D'(e_1(S)) - D'(e_2(S)) = -\frac{\alpha}{1-\alpha} D'(S)(\frac{1}{p} - 1)
\end{aligned} \tag{10}$$

which shows that $e_1(S) > e_1^*$ when $\frac{1}{p} < 1$ and $D'(S) > 0$, since the LHS has to increase, which can only happen if either $e_1(S)$ increases or $e_2(S)$ decreases – but if $e_2(S)$ decreases, then $e_1(S)$ necessarily increases in order for the task to be completed. She stops working when her current

[19] This underestimation in the domain of consumption choices would lead a person to consume goods too fast, since she would not realize how much more she would enjoy eating something once she is hungry rather than sated. This is exactly what Galak, Kruger, and Loewenstein (2013) find: people consume chocolates faster when they choose themselves when to eat, yet report enjoying them less.

perceived plan is equal to (or less than) what she has done, that is when $e_1(S) = S$. Substituting this into the above equations and some calculations, we get

$$D'(\tilde{e}_1)\left(\frac{1}{p} + \frac{\alpha}{1-\alpha}(\frac{1}{p} - 1)\right) = D'(\tilde{e}_2)$$
$$\iff \frac{D'(\tilde{e}_1)}{p}\frac{1-p\alpha}{1-\alpha} = D'(\tilde{e}_2$$

and so she acts as if her productivity was $\frac{1-\alpha}{1-p\alpha}p$, which is strictly more than p.

This result is a special case of the proposition~7.

Proposition 7. *Suppose a person allocates effort over T days and has to complete work E. The constraint is given by $E = \sum_{t=1}^{T} p_t \cdot e_t$, where p_t is her (known, exogenously given) productivity on day t. Denote by by $\tilde{E}_t^*$ the total amount of work done by the beginning of day t and by E_t^* the optimal total amount of work done at the beginning of day t.*

If p_t is strictly increasing and actual and optimal effort are determined by FOCs, then we have that $\tilde{E}_t^* < E_t^*$ $\forall t > 1$.

If p_t is strictly decreasing and actual and optimal effort are determined by FOCs, then denoting by $\tilde{E}_t^*$ the total amount of work done by the beginning of day t, we have that $\tilde{E}_t^* < E_t^*$ $\forall t > 1$.

Moreover, in both cases the person has time-inconsistent plans: at the end of day t, she overestimates how much work she will do on day $t+1$ (with the exception of the last day where she has to finish all remaining work). When productivity is increasing, this change of plan moves her further away from optimal effort that day; when productivity is decreasing, this change of plan moves her closer to optimal effort that day.

Since a person with constant productivity and exponential discounting with discount factor δ has FOCs that are identical to a person with exponentially increasing productivity with per-period productivity increases of $\frac{1}{\delta}$, the following corollary immediately follows.

Corollary 1. *Suppose a person allocates effort over T days and has to complete work E. The constraint is given by $E = \sum_{t=1}^{T} e_t$. She discounts utility exponentially by δ.*

Then we have that $\tilde{E}_t^* < E_t^*$ $\forall t > 1$, and moreover she has time-inconsistent effort allocation: at the end of day t she plans to work more on day $t+1$ than she will, and this change of plan moves her further away from optimal effort.

Here is an example of proposition 7 in action. Betsy has to complete an assignment that would take her $E = 18$ hours of work if each day she was as productive as she is today. Fortunately for her, she has lectures tomorrow and office hours the day after that: during lectures and office hours she will learn shortcuts for completing the problems on the assignment. Specifically, every hour of work done tomorrow is worth 1.5 hours of work today, while every hour of work done in two days is worth 1.5 hours of work tomorrow.

Obviously, she should work less today than tomorrow, since she will become more efficient at solving questions. Suppose that her disutility is quadratic. The optimal effort levels should satisfy the first order conditions $D'(e_1^*) = \frac{1}{p}D'(e_2^*) = \frac{1}{p^2}D'(e_3^*)$, which leads to $e_1^* \approx 2.2$, $e_2^* \approx 3.33$, and $e_3^* \approx 4.95$. On day 1, Betsy instead solves her perceived first order conditions, which we can derive as in the 2-day case to be $D'(\tilde{e}_1) = \frac{1-\alpha}{1-\alpha\frac{1}{p}}\frac{1}{p}D'(\tilde{e}_{2|1}) = \frac{1-\alpha}{1-\alpha\frac{1}{p^2}}\frac{1}{p^2}D'(\tilde{e}_{3|1})$, where $\tilde{e}_{i|1}$ indicates that it is the effort Betsy perceives to be optimal at the end of day 1. These are given by $\tilde{e}_1 \approx 1.52$, $\tilde{e}_{2|1} \approx 3.03$, and $\tilde{e}_{3|1} \approx 5.29$.

Yet, on day 2 she will not do what she thought she would do. She solves her new perceived first order condition, which is now exactly as in the 2-day case, taking into account that she worked roughly 1.52 hours on day 1: $D'(\tilde{e}_2) = \frac{1-\alpha}{1-\alpha\frac{1}{p}}\frac{1}{p}D'(\tilde{e}_3)$. Solving this, we find that $\tilde{e}_2 \approx 2.75$ and that $\tilde{e}_3 \approx 5.50$. Betsy was already planning to work less than she should, planning to do 3.03 instead of 3.33, yet she ends up doing even less, namely 2.75. Thus, Betsy postpones too much work, and thinks that she will have done more by the end of day 2 than will be the case. The reason is that Betsy wants to delay more effort, the more unpleasant effort is at that time. Betsy correctly understands that doing 1 minute less of work requires her to do 40 seconds more work tomorrow. Thus she saves 20 seconds, which she perceives as more unpleasant the more unpleasant effort is right now. Therefore she is willing to delay more work until tomorrow to take advantage of her higher productivity. Since tomorrow she will work more, she will be more tired at the end of the day when she decides to stop, and therefore she will want to delay more at the end of day 2 than at the end of day 1 and stops working earlier than anticipated.

Loewenstein, O'Donoghue, and Rabin (2003) highlighted the potential for projection bias to cause time inconsistent plans under habit formation, that is in a case where the utility from consumption decreases the more one has recently consumed. What my results highlight though is that projection bias can cause time-inconsistent behavior much more generally, in fact whenever there are incentives pushing away from equal effort over time. Moreover, it shows that this time-inconsistency occurs both when optimal effort is increasing or decreasing – and that while it in the direction of working less than planned for such monotonic effort sequences, the departure from earlier plans can improve choices when effort is decreasing.

It is important to note however that projection-bias leads to time-inconsistency only if the states in which choices are made are different. The intuition is thus more similar to temptation models such as Gul and Pesendorfer (2001) than to present-biased preferences (Laibson (1997); O'Donoghue and Rabin (1999)), what Ericson and Laibson (2019) call *unitary-self models.* Projection bias does not preferentially lead to present focus, although the time-inconsistent component of it tends to be overoptimistic because the final binding decision is made at the most tired time, yet most times people are more rested. Welfare-wise however, the earlier committed and higher-effort choice may be the mistake, rather than the immediate decision to lower effort. Nonetheless, through magnifying pre-existing present bias or focus, it is almost surely more likely to magnify such behaviors. And since this magnification is larger the more tired people are at the time of making committed choices, this may bias estimates of time preferences when comparing across populations or across times, with more tired populations appearing as more impatient – although careful laboratory designs can avoid such concerns by keeping (expected) tiredness constant across choice elicitations (see Fedyk (2018), Augenblick and Rabin (2019), Le Yaouanq and Schwardmann (2019)).

6 Concave Disutility

Until now I have assumed that the daily disutility D is convex, so that work becomes more unpleasant the longer a person works. While this is often correct, it is also true that some tasks become easier as we warm up or become focused, before eventually becoming harder as fatigue and boredom take over. Warm up is an integral part of both sports and music performance, and many tasks that require focus, such as writing or programming, get easier after an initial time of settling in. For this reason, in this section I explore daily disutility that, at least initially, is concave.

When a projection-biased person with concave disutility faces a single all-or-nothing task, she overestimates the task's disutility at the start of the day and therefore fails to do some worthwhile tasks. Let us consider the same situation as in section 3, where a high-school student named Alice has a deadline to finish a college application by midnight. Her daily disutility is $D(E) = 6 \cdot E - \frac{E^2}{2}$ for $E \leq 6$. The application takes her exactly 6 hours to complete and is worth $B = 20$. Since $\tilde{D}(6|0) = 27 > 18 = D(6)$, Alice decides not to complete the application: she is willing to start the application only if $B > 27$.

This result also holds when D is first concave and then convex. Concretely, suppose that $D(\cdot)$ is concave for $E < \bar{E}$ and convex on $E > \bar{E}$ for some $\bar{E} > 0$. Then there is a threshold E_L such that Alice overestimates the task's disutility if it takes fewer than E_L hours to complete, and she underestimates it if it takes more. We thus obtain the following proposition which, when the task is large enough, mirrors proposition 3 and, when the task is small enough, mirrors the preceding example.

Proposition 8. *Let D be concave for $E < \bar{E}$ and convex for $E > \bar{E}$, with $\bar{E} > 0$. The marginal disutility eventually becomes larger than it is initially: $\lim_{E\to\infty} D'(E) = \bar{D}$ with $\bar{D} > D'(0)$. A self-directed person faces an all-or-nothing task requiring effort E and paying B if completed. Let $\tilde{E}$ be the actual effort exerted and $U(\tilde{E}) = \mathbb{1}(\tilde{E} \geq E) \cdot B - D(\tilde{E})$ the total utility. Then there exist unique E_H and E_L with $E_H > E_L > \bar{E}$ and $D'(0) = \frac{D(E_L)}{E_L}$ such that the following hold:*

1. *$\forall E > E_L$, $\exists B$ s.t $\tilde{E} > 0$ and $U(E) < 0$.*

2. $\forall E < E_L$*,* $\exists B$ *s.t* $\tilde{E} = 0$ *and* $U(E) > 0$*.*

3. $\forall E < E_H$ *if* $\tilde{E} > 0$ *then* $\tilde{E} = E$*.*

4. $\forall E > E_H$*,* $\exists B$ *s.t.* $0 < \tilde{E} < E$*.*

Now suppose that we know that Alice will complete the application for sure, but she can take a break, whether to have coffee with a friend, respond to emails, or do homework. Since her disutility is concave, she should work without interruptions, unless the benefits B from taking a break are positive. Suppose that after 3 hours of work, a friend asks Alice if she wants to grab coffee. As we have seen in 6, Alice underestimates the change in disutility by a factor of $1 - \alpha = 0.5$. Thus, since the actual change in disutility from taking the break is 3 for each of the 3 hours she will have to do after the break, she perceives the increase in disutility to be $(1 - \alpha)(3 \cdot 3) = 4.5$ and joins her friend if $B > 4.5$, even though she should only do so if $B > 9$.

Now consider the case where Alice can work up to 6 hours on her application, with each hour of work having a benefit of 5. Then Alice may take a break expecting to continue working on the application afterwards, yet fail to resume the task. She starts the application, since $5 \cdot 6 = 30 > 27 = \tilde{D}(6|0)$. After 3 hours of work, her friend again asks her if she wants to have a break. If she takes a break, she will fail to resume the task, since her perception of resuming again will be $\tilde{D}(3|0) = \frac{1}{2}(D(3) + D'(0) \cdot 3) = \frac{1}{2}(13.5 + 18) = 15.25 > 15 = 3 \cdot 5$. But after 3 hours of work, Alice mistakenly thinks that she will resume the task, since she currently perceives the disutility of completing 3 hours after the break as $\tilde{D}(3|3) = \frac{1}{2}(13.5 + D'(3) \cdot 3) = 11.25 < 15$. As we just saw, she thinks that the increase in disutility from taking the break is only 4.5 and thus takes a break if the benefits exceed 4.5. Since she doesn't resume the task, she in fact is worse of by $3 \cdot 5 - (D(6) - D(3)) = 11.5$, so that if $B \in (4.5, 11.5)$ she is strictly worse off from taking the break.

Moreover, Alice may fail to resume a task even if the task becomes easier only over very short time intervals – if $\bar{E}$ is small. To take an extreme example, suppose $D'(0) = 6$ and $D'(E) = 2\ \forall E > 0$, so that the task is instantaneously easier after Alice gets started. Then as long as Alice resumes the task, she doesn't incur any costs. But because there are no costs incurred from resuming, she always thinks that she will resume the task if she currently would continue, and therefore she will take every opportunity for beneficial breaks, even though she may not resume the task, since she overestimates the disutility when she has to start.

One way that Alice can overcome the failure to start a worthwhile task is to front-load benefits. Let us stick with the example where $D'(0) = 6$ and $D'(E) = 2\ \forall E > 0$. Suppose the benefits per hour are b and that Alice can work for at most 6 hours on the task. Then she perceives the task worthwhile doing if $b > 4 = \tilde{D}'(E|0)$, and not worthwhile if $b < 4$, even though it is worth doing as long as $b > 2$. If instead, Alice perceived the rewards of the first hour to be $b + 1$ and the rewards of the other hours to be equal to $b - \frac{1}{5}$, then she would start working for $b > 3$ – and once she starts working, she will continue to work as long as $b - \frac{1}{5} > 2$. In short, Alice would complete all 6 hours if $b > 3$, even though the total benefits from doing so did not increase. Whenever Alice doesn't start a worthwhile task, there is a way to front-load benefits (without raising total benefits) such that Alice completes all the work.

7 Discussion and Conclusion

Throughout the paper, I made three assumptions on the instantaneous disutility. First I assumed that a person either works or doesn't work, ruling out intensity of effort. Second I assumed that the instantaneous disutility depends only on total time a person has worked so far, ruling out breaks and rest during a day. And third, I assumed that people know their disutility, but misperceive it. I now discuss each of these assumptions in turn.

It is straightforward to extend the results in sections 3 and 4 to allow for intensity of effort. These results rely on the person being overly optimistic when work is currently easy and overly pessimistic when it is currently hard, which remains true when we allow for intensity of effort. In the notation of section 2, the instantaneous disutility is $D(e, s)$ where e is no longer restricted to 0 or 1, and a projection-biased person perceives her future instantaneous disutility as $\tilde{d}(e, s|s_0) = (1-\alpha)D(e, s) + \alpha D(e, s_0)$ when she is in state s_0. If $D(e, s)$ is increasing in s, then a person starts some all-or-nothing tasks that are overly ambitious, yet may quit once she becomes tired. She will also work too much on time-sensitive tasks when multi-tasking, underestimating how soon she will stop working on other tasks afterwards.

On the other hand, the results in section 5 do change in meaningful ways. Whereas in the simple framework, a person can only change the timing of effort by working more on one day – by changing the extensive margin of time – now she can also work more on a given day by working at a higher intensity – by changing the intensive margin. When a person responds to changes in incentives and opportunity costs primarily along the extensive margin – by working longer, but not harder – the results in section 5 hold: the person overreacts to incentives and opportunity costs, working too much on days where incentives are higher or costs lower. If however, she responds primarily along the intensive margin, this need no longer be true. Consider, to take the extreme case, a person who has to work for exactly 8 hours every day, but can choose the intensity of effort at every moment. She has to complete an all-or-nothing task, requiring a fixed amount of work, so that she only decides when to work, but not how much. Then, at the end of the first day, being tired she underestimates how easy work will be the next day and therefore works more on the first day, even when there are no incentives to do so and no differences in opportunity cost of time. Thus the intensive margin has new implications, and may push behavior in a different direction from the extensive margin studied in section 5.

Let us now relax the assumption of no rest during a day and consider a person who can take a fixed number of breaks in a day. This is identical to the situation analyzed in section 4. The main lesson from section 4 was that repeated fluctuations in plans can lead to inconsistent behavior with large welfare consequences for all-or-nothing tasks, and that people are systematically overly optimistic about how well they will complete long-term tasks with decreasing returns to effort. If a person can take breaks during a day, these results extend to daily tasks. Since a person doesn't become fully rested after a break and can choose how many breaks to take, the fluctuations in marginal disutility during a day will be less severe than those studied in section 4, which may attenuate – but not reverse – these results.

Finally, people are often uncertain about their disutility of effort, in which case a projection-biased person may mislearn what her actual disutility is. She may mistakenly attribute her dislike of a task she always does when tired to the task itself, rather than to the fact that she is always tired when doing it. This may lead to the type of attribution bias as described in Haggag et al. (2019). This type of incorrect belief updating may lead her to become too confident that some tasks are better than others – or fail to realize that this is the case.

All of this suggests that the basic logic drawn out in this paper – the repeated fluctuation between overly optimistic and pessimistic, the inconsistent plans, the inefficient effort allocation – are robust to extensions that allow for effort intensity and flexible breaks.

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A Proofs

A.1 Proofs for Section 3

Proof of proposition 1.

Proof. A projection-biased person solves the same maximization problem as an unbiased person, but perceives her disutility to be $\tilde{D}(.|S)$ at time S. The first order condition thus depends on time S:

$$\tilde{D}'(\tilde{E}^*(S)|S) = B'(\tilde{E}^*(S)) \iff (1-\alpha)D'(\tilde{E}^*(S)) + \alpha D'(S) = B'(\tilde{E}^*(S))$$

Let E^* be the optimal level of effort, so that $D'(E^*) = B'(E^*)$. Then $S < E^* \implies D'(S) < D'(E^*) \implies \tilde{D}'(E^*|S) < D'(E^*) = B'(E^*)$. Hence, since $\tilde{D}'(\tilde{E}^*(S)|S) = B'(\tilde{E}^*(S))$ and since $B(\cdot)$ is concave and $\tilde{D}(\cdot|S)$ is strictly convex, we have that $\tilde{E}^*(S) > E^*$. Similarly, if $S = E^*$, then $\tilde{D}'(E^*|S) = D'(E^*) = B'(E^*)$, so E^* satisfies the FOC when $S = E^*$ and hence is perceived as the optimal time for stopping. Thus as long as the person has worked less than E^*, she plans to work more than E^* and continues working, and once she has worked E^* she stops. □

Proof of proposition 2:

Proof. The person – by assumption – first works on the first task, and then on the second task. As long as she works on first task she solves the following first order conditions:

$$\tilde{D}'(\tilde{E}_1^*(S) + \tilde{E}_2^*(S)|S) = B_1^{'}(\tilde{E}_1^*(S)) = B_2^{'}(\tilde{E}_2^*)$$

She switches to the second task when the amount she has worked on the first task so far, S, is equal to how much she thinks at that time she should optimally work on the first task, $\tilde{E}_1^*(S)$. Let $\tilde{E}_1^*$ be the actual time by which she switches to the second task , which thus satisfies the first order condition with $S = \tilde{E}_1^*$:

$$\tilde{D}'(\tilde{E}_1^* + \tilde{E}_{2|1}^*|\tilde{E}_1^*) = B_1^{'}(\tilde{E}_1^*) = B_2^{'}(\tilde{E}_{2|1}^*)$$

where $\tilde{E}_{2|1}^*$ is the amount she plans to work on task 2 when she switches. Note that when $B_1^{'}(\tilde{E}_1^*) = B_2^{'}(\tilde{E}_{2|1}^*)$ then the following are equivalent: $\tilde{E}_1^* > E_1^*$; $\tilde{E}_{2|1}^* > E_2^*$; and $\tilde{E}_1^* + \tilde{E}_{2|1}^* > E_1^* + E_2^*$, since the B_i^* are strictly concave and disutilities are strictly convex. That is, if she plans to work more on the first task than is optimal, then she also plans to work more on the second task than is optimal and vice versa; and hence both of this imply and are implied by her planning to work more in total than is optimal.

We can now show that $\tilde{E}_1^* > E_1^*$. Suppose not. Then she plans to work less in total than is optimal and we get:

$$
\begin{aligned}
\tilde{D}'(\tilde{E}_1^* + \tilde{E}_{2|1}^* | \tilde{E}_1^*) &< \tilde{D}'(\tilde{E}_1^* + \tilde{E}_{2|1}^* | \tilde{E}_1^* + \tilde{E}_{2|1}^*) \\
&= D'(\tilde{E}_1^* + \tilde{E}_{2|1}^*) \\
&\leq D'(E_1^* + E_2^*), \text{ since total optimal effort is larger then total planned effort} \\
&= B'(E_1^*) \\
&\leq B'(\tilde{E}_1^*), \text{ since } \tilde{E}_1^* \leq E_1^*
\end{aligned}
$$

which shows that it does not satisfy the first order condition. Thus $\tilde{E}_1^* > E_1^*$.

Once she switches, she keeps working on the second task. While she wants to reduce E_1, she can no longer do so, and thus takes $\tilde{E}_1^*$ as a given. Thus she now simply solves the first order condition

$$
\tilde{D}'(\tilde{E}_1^* + \tilde{E}_2^*(S)|S) = B_2^{'}(\tilde{E}_2^*(S))
$$

and as before, she stops once this holds her current S equal to final total effort, $S = \tilde{E}_1^* + \tilde{E}_2^*$:

$$
\begin{aligned}
&\tilde{D}'(\tilde{E}_1^* + \tilde{E}_2^* | \tilde{E}_1^* + \tilde{E}_2^*) = B_2^{'}(\tilde{E}_2^*) \\
&\iff D'(\tilde{E}_1^* + \tilde{E}_2^*) = B'(\tilde{E}_2^*) \\
&\iff D'(\tilde{E}_1^* + \tilde{E}_2^*) - B'(\tilde{E}_2^*) = 0 \\
&\iff D'(E_1^* + x + \tilde{E}_2^*) - B'(\tilde{E}_2^*) = 0 \text{ for } x = \tilde{E}_1^* - E_1^* > 0
\end{aligned}
$$

Since $B'(\tilde{E}_2^*) = D'(E_1^* + E_2^* + x) > D'(E_1^* + E_2^*) = B'(E_2^*)$, we have that $\tilde{E}_2^* < E_2^*$. Therefore, $D'(\tilde{E}_1^* + \tilde{E}_2^*) = B'(\tilde{E}_2^*) > B'(E_2^*) = D'(E_1^* + E_2^*)$, so that $\tilde{E}_1^* + \tilde{E}_2^* > E_1^* + E_2^*$ and we are done. $\square$

Here is the proof of proposition 3.

Proof. Let $\tilde{R}(E|S) := \tilde{D}(E|S) - \tilde{D}(S|S)$, the perceived remaining disutility of completing the task after S hours of work have already been completed. Notice that the person works as long as $\tilde{R}(E|S) < B$ and never works when $\tilde{R}(E|S) > B$.

The first part of the proposition claims that for all $E > 0$, it is possible to find a $B > 0$ such that the person starts working on the task. Notice that $\tilde{D}(E|0) = (1-\alpha)D(E) + \alpha D'(0) \cdot E < D(E)$ since $D(E) = \int_0^E D'(S)dS > \int_0^E D'(0)dS$, as $D(\cdot)$ is strictly convex and $E > 0$. Pick $B \in (\tilde{D}(E|0), D(E))$. Then, since $\tilde{R}(E|0) = \tilde{D}(E|0)$ and since $\tilde{R}(E|S)$ is continuous in S, we have that $\tilde{R}(E|\varepsilon) < B$ for some sufficiently small $\varepsilon > 0$, so that the person will work at least for a time ε. This proves the first part of the proposition.

Now define $\tilde{R}^*(E) := \max_{S \in [0,E]} \tilde{R}(E|S)$, that is, the worst perceived remaining disutility of completing the task. Of course, for an unbiased person, the worst remaining disutility is always at the start when the most work remains to be done, but this won't necessarily hold for projection-biased people. Notice that if $\tilde{R}^*(E) < B$, then the remaining task is always perceived worth doing and therefore is completed. If $\tilde{R}^*(E) > B$, then the task is definitely not completed, since at some point the person perceives it not worth doing. Finally, if $\tilde{R}(E|0) < B$ and $\tilde{R}^*(E) > B$, then the person starts the task, but does not complete it.

Let $\mathcal{E} := \{E \geq 0 : \tilde{R}^*(E) > \tilde{R}(E|0)\}$. I will show that $\mathcal{E} = (E_H, \infty)$ for some finite $E_H > 0$, which proves that if $E > E_H$, then we can pick B in the non-empty interval $(\tilde{R}(E|0), \tilde{R}^*(E))$ and the person starts the task but fails to complete it. Moreover, I will show that if $E < E_H$, then $\tilde{R}(E|0) > \tilde{R}(E|S)\ \forall S \in (0, E]$, which means that, for such tasks, if the person starts the task, she also completes it.

First, let us show that $\mathcal{E}$ is not the empty set. Pick some $S > 0$ such that $D'(S) > 0$. Notice that $\tilde{R}(E|S) - \tilde{R}(E|0) = \tilde{D}(E|S) - \tilde{D}(S|S) - \tilde{D}(E|0) = (1-\alpha)(D(E) - D(S) - D(E)) + \alpha E(D'(S) - D'(0)) + \alpha S D'(S) = -D(S)(1-\alpha) + \alpha S D'(S) + \alpha E(D'(S) - D'(0))$. Since $D'(S) - D'(0) > 0$, this expression becomes positive for sufficiently large E, say for $E > \bar{E}$, so that $\tilde{R}(E|S) - \tilde{R}(E|0) > 0$ for all $E > \bar{E}$. Thus $\mathcal{E}$ is not empty.

Further, from $\tilde{R}(E|S) - \tilde{R}(E|0) = -D(S)(1-\alpha) + \alpha S D'(S) + \alpha E(D'(S) - D'(0))$ we immediately see that this expression is strictly increasing in E. Hence if $\tilde{R}^*(E) - \tilde{R}(E|0) > 0$ and $E' > E$, then there is some S s.t. $\tilde{R}(E|S) - \tilde{R}(E|0) > 0$ by definition of $\tilde{R}^*(E)$. Thus $\tilde{R}(E'|S) - \tilde{R}(E'|0) > 0$ and thus $\tilde{R}^*(E') - \tilde{R}(E'|0) > 0$.

Therefore if $E \in \mathcal{E}$, then $E' \in \mathcal{E}$. Let $E_H = \liminf \mathcal{E}$. Then if $E > E_H$, by definition of E_H, there is some $E' \in (E_H, E)$ s.t. $E' \in \mathcal{E}$. Therefore all $E > E_H$ are in $\mathcal{E}$.

Moreover, $E_H \notin \mathcal{E}$, since either $E_H = 0$ (in which case it is obvious) or $E_H > 0$. If $E_H > 0$ and $E_H \in \mathcal{E}$, then $\tilde{R}(E_H|S) > \tilde{R}(E_H|0)$ for some $S > 0$, and thus $\tilde{R}(E_H - \varepsilon|S) > \tilde{R}(E_H - \varepsilon|0)$ for sufficiently small ε, which implies that $E_H - \varepsilon \in \mathcal{E}$. This contradicts the definition of E_H as $\liminf \mathcal{E}$.

Finally, note that when $E < E_H$, we must have that $0 > \tilde{R}(E|S) - \tilde{R}(E|0)\ \forall S > 0$. If not, then $\tilde{R}(E|S) - \tilde{R}(E|0) = 0$ for some S and we know that the LHS strictly increases in E, which would imply that $E_H \in \mathcal{E}$. And thus we are done.

□

A.2 Proofs for Section 4

A.2.1 Proofs of Results on Multi-Day All-or-Nothing Task

In the first part of this section, I prove the propositions 4 and **??** for a continuous-time version of the task, which I show in the second part to be the limit case as $T \to \infty$, which then proves the original propositions.

Proofs of Results on Multi-Day All-or-Nothing Task: Continuous Time Setup

First, I need some notation to talk succinctly about tasks and I need to define the continuous-time problem.

Definition 7. *A discrete-time task requiring total effort $E_0 \cdot T$, paying rewards $B_0 \cdot T$ if completed by the end of day T is written as task (E_0, B_0, T). A continuous-time task requiring total effort E_0 and paying total rewards B_0 if completed by time 1 is written as (E_0, B_0).*

Definition 8. *Consider a person facing a task (E, B, T). Then the* continuous time problem *corresponding to this discrete time problem is as follows. At every time $x \in [0, 1)$ a person chooses instantaneous (flow) effort e_x, based on receiving total benefits B for completing total effort E by time $x = 1$. Let E_x for $x \in [0, 1)$ be the effort remaining at time x – that is $E_x = E - \int_0^x e_{x'} dx'$.*

The initial condition is $E_0 = E$ and a task is completed if $E_1 = 0$. Instantaneous effort e_x satisfies the following:

$$e_x = \begin{cases} 0, \text{ if } G(x, 0, E_x) > B \\ \frac{E_x}{1-x}, \text{ if } G(x, \frac{E_x}{1-x}, E_x) < B \\ e_x^* \text{ otherwise, with } G(x, e_x^*, E_x) = B \end{cases}$$

where $G(x, s, E) = (1-\alpha)(1-x) \cdot D(\frac{E}{1-x}) + \alpha D'(s)E$.

When $G(x, e_x^*, E_x) = B$, we have $e_x^* = f(x, E, B) := (D')^{-1}\left(\frac{B-(1-\alpha)(1-x)D(E)}{\alpha E}\right)$, with $f(\cdot)$ existing by strict convexity of $D(\cdot)$.

Notice that e_x solves a similar maximization problem, as if at instant x she did work more and more and perceive effort at later times as more costly. Intuitively, the difference with the discrete time setup is that we do not need to take into account that the more a person has worked, the less work there remains to do, since the instantaneous work doesn't matter, which ensures that the perceived remaining disutility always increases during the 'period' at time x. Readers who do not like this interpretation can simply treat the continuous time problem as an analytical device.

The proofs will refer to the times τ_0 and τ_F, which are (roughly) the total time a person spends not working at all or the total time a person works efficiently *given* how much she worked up to a given time x. Formally and concretely, we have the following definition:

Definition 9. *Let $\tau_0(E_0, B_0) := \liminf\{\tau \in [0,1] : G(x, 0, E_x(E_0, B_0)) < B_0 \ \forall x < 1-\tau\}$ – intuitively (but not quite) the time before the end when the person stops working entirely.*

Let $\tau_F(E_0, B_0) := \liminf\{\tau \in [0,1] : G(x, \frac{E_x(E_0,B_0)}{1-x}, E_x(E_0, B_0)) > B_0 \ \forall x < 1-\tau\}$ – intuitively (but not quite) the time before the end when the person starts completing the task efficiently.

With this, let us first prove that $E_x(E_0, B_0)$ for $x < 1$ is Lipschitz continuous in a neighborhood of (E_0, B_0, x) and that it is increasing in E_0.

I will use the following theorem (from https://www.math.washington.edu/~burke/crs/555/555_notes/continuity.pdf) to prove continuity.

Theorem 1. *Consider the initial value problem*

$$x' = f(t, x, \mu), \;\; x(t_0) = y$$

where x' is the derivative of $x(t)$ with respect to time. If f is continuous in t, x, μ and Lipschitz in x with Lipschitz constant independent of t and μ, then $x(t, \mu, y)$ is continuous in (t, μ, y) jointly.

Then we get continuity as follows:

Lemma 2. *Suppose that $D''(x) > d$ for some $d > 0$. The solution $E_x(E, B)$ to the continuous-time problem restricted to $x \in [0, 1-\varepsilon]$ with $\varepsilon > 0$ exists and is Lipschitz continuous in x, E, and B, on $[0, 1-\varepsilon] \times [\underline{E}, \bar{E}] \times [0, \infty]$, for some $\bar{E} > \underline{E} > 0$.*

Proof. It is clear that $E_x \leq E_0$, so we can pick $\bar{E} > E_0$. We then show that, starting with $E_0 \in [\underline{E}, \bar{E}]$, we will not fall below $\underline{E}$ before time x. Given that the maximum instantaneous effort is given by $\frac{E_x}{1-x}$ it is not hard to see that at most a fraction x of the total effort will be completed by time x (the efficient amount, conditional on trying to complete the task).[20] Thus if $E_0 \geq \frac{1}{\varepsilon}\underline{E}$, then E_x will be larger than $\underline{E}$ for all $x \leq 1-\varepsilon$.

We have that $\dot{E}_x = -e(x, E_x, B)$ with

$$e(x, E_x, B) = \begin{cases} 0, \text{ if } G(x, 0, E_x) > B \\ \frac{E_x}{1-x}, \text{ if } G(x, \frac{E_x}{1-x}, E_x) < B \\ f(x, E_x, B) \text{ otherwise} \end{cases}$$

where $G(x, s, E) = (1-\alpha)(1-x) \cdot D(\frac{E}{1-x}) + \alpha D'(s)E$, and $f(x, E, B) := (D')^{-1}\left(\frac{B-(1-\alpha)(1-x)D(E)}{\alpha E}\right)$. Given theorem 1, we only need to show that $e_x(x, E, B)$ is continuous in t, E, and B, and Lipschitz continuous in E indpendent of t and B. Notice that G and f are continuous functions, given that x is bounded away from 1 and E is bounded away from 0.

First, notice that when $G(x, 0, E) = B$, by definition of G and f we have that $f(x, E, B) = (D')^{-1}(D'(0)) = 0$, and similarly when $G(x, \frac{E}{1-x}, E) = B$, we have that $f(x, E, B) = \frac{E}{1-x}$. Thus $e(x, E, B)$ restricted to $A := \{(x, E, B) : G(x, 0, E) \geq B\}$ is the constant 0 function, $e(x, E, B)$ restricted to $B := \{(x, E, B) : G(x, \frac{E}{1-x}, E) \leq B\}$ is equal to $\frac{E}{1-x}$, and $e(x, E, B)$ restricted to $C := \{(x, E, B) : G(x, 0, E) \leq B \text{ and } G(x, \frac{E}{1-x}, E) \geq B\}$ is equal to $f(x, E, B)$.

If we can show that $e(x, E, B)$ restricted to $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$ is Lipschitz in all parameters (which is stronger than what we need), then $e(x, E, B)$ is Lipschitz continuous in all parameters over the union of $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$. The reason is that all three regions are closed, and thus contain their limit points: Suppose we have two points $\boldsymbol{x} = (x, E, B)$ and $\boldsymbol{x'} = (x', E', B')$ and we want to show that $|e(x, E, B) - e(x', E', B')| < K(|x-x'|+|E-E'|+|B-B'|)$ for some K. First, if both points are in the same region, then this immediately holds, by the assumption that the function is Lipschitz in that region. Now suppose that the two points are in regions $\mathcal{A}$ and $\mathcal{C}$. These two regions share a common border. Thus there exists some point $\boldsymbol{x''} = (x'', E'', B'') = \kappa \cdot \boldsymbol{x} + (1-\kappa) \cdot \boldsymbol{x'}$ on the line connecting the two points that belongs to both regions (this is the part that requires both $\mathcal{A}$ and $\mathcal{C}$ to be closed), so that $|e(x, E, B) - e(x', E', B')| = |e(x, E, B) - e(x'', E'', B'') + e(x'', E'', B'') - e(x', E', B')| \leq |e(x, E, B) - e(x'', E'', B'')| + |e(x'', E'', B'') - e(x', E', B')| < K(|x - x''| + |E - E''| + |B - B''| + |x'' - x'| + |E'' - E'| + |B'' - B'|) = K(|x-x'|+|E-E'|+|B-B'|)$, where $|x-x''|+|x''-x'| = |x-x'|$ because the point $\vec{x''}$ lies between the two points (is a convex combination of) $\boldsymbol{x}$ and $\boldsymbol{x'}$. Thus the function is Lipschitz continuous over the union of $\mathcal{A}$ and $\mathcal{C}$, and by an exactly identical argument over the union of the three regions.

Restricting ourselves to $E_0 \in [\underline{E}, \bar{E}]$, it is clear that $e(x, E, B)$ is Lipschitz on A, where it is constant. It is equally clear that $e(x, E, B)$ is Lipschitz continuous on B since (by assumption) we are only considering $x \leq 1-\varepsilon$, that is $1-x \geq \varepsilon$.

Finally, $e(x, E, B)$ is Lipschitz continuous on C if $f(\cdot)$ is. But $f(\cdot)$ is the inverse of $D'(\cdot)$, so as long as the derivative of $D'(\cdot)$ is strictly bounded away from 0 everywhere, $f(\cdot)$ is Lipschitz. This holds since we assume $D''(x) > d$ for some $d > 0$. Thus we have shown that $e(x, E, B)$ is Lipschitz continuous when $x \leq 1-\varepsilon$, $E \in [\underline{E}, \bar{E}]$ and $B \geq 0$, for any $\varepsilon > 0$, $\underline{E} > 0$, $\bar{E} > 0$. $\square$

[20] This statement is proved in Lemma 5

Lemma 3. *If $G(x,0,E_x) > B$, then $G(x',0,E_{x'}) > B$ for all $x' \geq x$. Similarly, if $G(x, \frac{E_x}{1-x}, E_x) < B$, then $G(x', \frac{E_{x'}}{1-x'}, E_{x'}) < B$ for all $x' \geq x$.*

Proof. Suppose not. Then there exists $1 > x' > x$ such that $G(x',0,E_{x'}) \leq B$. Note that by lemma 2, E_x is continuous on $[0, x'+\varepsilon]$ for sufficiently small ε, and because G is continuous in all its arguments, we know that $G(x+\varepsilon_1, 0, E_{x+\varepsilon_1}) > B$ for sufficiently small ε_1. Thus for $x^* := \liminf\{x' > x : G(x',0,E_{x'}) \leq B\}$, we have $x^* > x$. Moreover, $G(y,0,E_y) > B$ for all $x \leq y < x^*$ and therefore $e_y = 0$. Thus $E_{x^*} = E_x - \int_x^{x^*} e_y dy = E_x$. Hence we have that $G(x^*,0,E_{x^*}) = G(x^*,0,E_x) > G(x,0,E_x) > B$, since G is strictly increasing in x.[21] But then by continuity of E_x and G, we have that $G(x^*+\varepsilon_2, 0, E_{x^*+\varepsilon_2}) > B$ for sufficiently small ε_2, which contradicts the definition of x^*.

A similar argument works for the second part of the lemma. □

Now let us prove that E_x is increasing in E_0:

Lemma 4. *For a fixed $x < 1$ and $B_0 > 0$, $E_x(E_0, B_0)$ is strictly increasing in E_0.*

Proof. Let $\Delta_x = E_x(E_0', B_0) - E_x(E_0, B_0)$ for some $E_0' > E_0 > 0$. We need to show that $\Delta_x > 0$ for all $x < 1$.

Notice that $\Delta_0 = E_0' - E_0 > 0$ and that $\frac{d\Delta}{dx} = -e_x' + e_x$. Since E_x is continuous, we have that $\Delta_x > 0$ for all $x < \varepsilon$ at least. Suppose that the claim is false, so that $x^* := \liminf\{x : \Delta_{x^*} \leq 0\}$ exists. Then $x^* \geq \varepsilon > 0$ and for all $x < x^*$ we have $\Delta_x > 0$. Thus $E_x' > E_x$.

We then have check that for all possible cases of values for e_x, we can limit how large $e_{x'}$ is. If $G(x,0,E_x) > B$, then $G(x,0,E_x')$, and hence $e_x = e_x' = 0$. If $G(x,e_x,E_x) = B$, then $G(x,e_x,E_x') > B$, since G is increasing in E, and therefore $e_x' < e_x$ because G is increasing in its second argument. Finally, if $G(x, \frac{E_x}{1-x}, E_x) < B$, then $e_x = \frac{E_x}{1-x}$ and $e_x' \leq \frac{E_x'}{1-x}$.

Thus we see that in all cases $\frac{d\Delta_x}{dx} = -e_x' + e_x \geq \frac{-E_x'+E_x}{1-x} = -\frac{\Delta_x}{1-x}$, and therefore for $x < x^*$ $\Delta_{x^*} = \Delta_x + \int_x^{x^*} \frac{d\Delta_x}{dx} dx \geq \Delta_x - \int_x^{x^*} \frac{\Delta_y}{1-y} dy$. Let $\delta < \frac{1}{2}(1-x^*)$. We know by the definition of x^* that $\Delta_x > 0$ for $x < x^*$. Pick $x \in [x^*-\delta, x^*)$ that achieves the maximum of Δ_x in this interval, which exists since Δ_x is continuous. Then we have that $\Delta_{x^*} \geq \Delta_x - \int_x^{x^*} \frac{\Delta_y}{1-y} dy \geq \Delta_x - \Delta_x \frac{\delta}{1-x^*} > \frac{1}{2}\Delta_x > 0$. Thus $\Delta_{x^*} > 0$ and therefore (by continuity) $\Delta_{x^*+\varepsilon} > 0$ for some small $\varepsilon > 0$, which contradicts the definition of x^*. Thus the claim is proved. □

Lemma 5. *$E_x(E_0,B_0) \geq E_{x'}(E_0,B_0)\frac{1-x}{1-x'}$ for $1 > x > x' \geq 0$, and $E_x(E_0,B_0)$ is decreasing in B_0.*

[21] G is strictly increasing in x because $(1-x) \cdot D(E/(1-x)) = E \cdot 1/X \cdot D(X)$ where $X = (1-x)/E$. But $D(X)/X$ is the average disutility per unit of effort, which strictly increases for a strictly convex function $D(\cdot)$.

Proof.

$$
\begin{aligned}
\dot{E}_x \geq \frac{E_x}{1-x} &\implies \frac{\dot{E}_x}{E_x} \geq -\frac{1}{1-x} \\
&\implies \frac{d}{dx}\log(E_x) \geq -\frac{1}{1-x} \\
&\implies \log(E_{x'}) - \log(E_x) \geq -\int_x^{x'} \frac{1}{1-y}dy \\
&\implies \log(\frac{E_{x'}}{E_x}) \geq \int_x^{x'} \frac{d}{dy}\log(1-y)dy \\
&\implies \log(\frac{E_{x'}}{E_x}) \geq \log\frac{1-x}{1-x'} \\
&\implies \frac{E_{x'}}{E_x} \geq \frac{1-x}{1-x'}
\end{aligned}
$$

The proof that $E_x(E_0, B_0)$ is decreasing in B_0 is similar to the proof of lemma 4, and thus I omit it. $\square$

Now let us prove that $\tau_0(E_0, B_0)$ and $\tau_F(E_0, B_0)$ are continuous in E_0.

Lemma 6. *Suppose $D'(E) \to \infty$ as $E \to \infty$ and $D''(\cdot) > d$ for some $d > 0$. If $\tau_0(E_0, B_0) \in (0,1)$, then $\tau_0(E, B)$ is continuous in (E, B) in a neighborhood of (E_0, B_0), increasing in E and decreasing in B. If $\tau_F(E_0, B_0) \in (0,1)$, then $\tau_F(E, B)$ is continuous and decreasing in (E, B) in a neighborhood of (E_0, B_0), decreasing in E and increasing in B.*

Proof. The proofs are essentially identical for τ_0 and τ_F, so I only prove the first. Remember that

$$\tau_0(E_0, B_0) = \liminf\{\tau : 1-\tau \in [0,1] \text{ and } G(x, 0, E_x(E_0, B_0)) < B_0 \ \forall x < 1-\tau\} = \liminf \Gamma_0$$

Notice that $1 \in \Gamma_0$, thus τ_0 always exists. Suppose $\tau_0 \in (0,1)$. Then take $x > 1-\tau_0$. Suppose $E_0^{'} > E_0$ and let $\tau_0 := \tau_0(E_0, B_0)$ and $\tau_0^{'} := \tau_0(E_0^{'}, B_0)$ and similarly for Γ_0 and $\Gamma_0^{'}$. Note that if $G(x, 0, E_x(E_0, B_0)) > B_0$ then, by lemma 4, $E_x^{'} \geq E_x$, and thus (since G is increasing in its third argument) $G(x, 0, E_x(E_0, B_0)) > B_0$. Therefore for $\tau \notin \Gamma_0$, then there exists some $x < 1-\tau$ with $G(x, 0, E_x) \geq B_0$ and therefore $G(x, 0, E_x^{'}) > B_0$ so that $\tau \notin \Gamma_0^{'}$. Hence $\Gamma_0^{'} \subset \Gamma_0$ and thus $\tau_0^{'} \geq \tau_0$.

Notice that as we increase B_0 to $B_0^{'}$, every τ in Γ_0 is necessarily also in $\Gamma_0^{'}$: if $G(x, 0, E_x(E_0, B_0)) < B_0$, then $G(x, 0, E_x(E_0, B_0^{'})) < B_0^{'}$, since E_x weakly decreases in B_0, and thus $G(\cdot)$ decreases, while the RHS increases. Thus $\Gamma_0 \subset \Gamma_0^{'}$, hence $\tau_0^{'} \leq \tau_0$.

Let us now show continuity. Fix (E_0, B_0), then τ_0 is s.t. for $x < 1-\tau_0$ we have $G(x, 0, E_x(E_0, B_0)) < B_0$ and for every $\varepsilon > 0$ there is some $x \in (1-\tau_0, 1-\tau_0+\varepsilon)$ with $G(x, 0, E_x(E_0, B_0)) \geq B_0$. Suppose by contradiction that τ_0 is not continuous. Then there is some δ s.t. for every ε_i we have (E_i, B_i) within ε_i distance from (E_0, B_0) with either some $x_i \leq 1-\tau_0-\delta$ and $G(x_i, 0, E_{x_i}(E, B)) \geq B$ so that $\tau_0^{'} \geq \tau_0 + \delta$, or we have for all $x < 1-\tau_0+\delta$ we have $G(x, 0, E_x(E, B)) < B$, so that $\tau_0^{'} \leq \tau_0 - \delta$.

Contradiction Case 1: For $\varepsilon_i \to 0$, there is a sequence (E_i, B_i) s.t. $G(x, 0, E_x(E_i, B_i)) < B_i$ for all $x < 1-\tau_0+\delta$.

Since $E_x(E, B)$ is (Lipschitz) continuous in (E, B) and $G(\cdot)$ in its arguments in the range observed, this converges uniformly for all $x < 1 - \tau_0 + \delta$. Applying this to the closed range $x < 1 - \tau_0 + 1/2\delta$, we find that $G(x, 0, E_x(E_0, B_0)) < B_0$ for all $x < 1 - \tau_0 + 1/2\delta$, which contradicts the value of τ_0.

Contradiction Case 2: For $\varepsilon_i \to 0$, there is a sequence (E_i, B_i) and some $x_i \leq 1 - \tau_0 - \delta$ s.t. $G(x, 0, E_x(E_i, B_i)) \geq B_i$.

Given that the ranges are all finite, (E_i, B_i, x_i) converges to (E_0, B_0, x), with $x \leq 1 - \tau_0 - \delta$, with $G(x, 0, E_x(E_0, B_0)) \geq B_0$. But this directly contradicts the definition of τ_0, since this implied that $G(x, 0, E_x(E_0, B_0)) < B$ for all $x < 1 - \tau_0$.

Hence $\tau_0(E, B)$ is continuous in (E, B) □

Now let us prove the equivalent to proposition 4 but for continuous time tasks. Let us split the proof in two parts.

Proposition 9. *The disutility of effort is strictly convex. Consider a task (E_0, B_0) with $E_0 > 0$ fixed. Then there exist $B_H(E_0) > B_C(E_0) > B_L(E_0) > 0$ such that*

- *if $B > B_H$, then the task is completed efficiently, i.e. $\tau_F = 1$.*
- *if $B_H > B > B_C$, then $\tau_F(E_0, B_0) \in (0, 1)$ and the task is completed.*
- *if $B_C > B > B_L$, then $\tau_0(E_0, B_0) \in (0, 1)$ and the task is not completed.*
- *if $B_L > B$, then no effort is spent on the task, i.e. $\tau_0 = 1$.*

Proof. Let $B_L = (1 - \alpha)D(E_0) + \alpha D'(0)E_0$. Then $G(0, 0, E_0) = B_L$ and therefore if $B < B_L$ we have $G(0, 0, E_0) > B_L$ and hence by lemma 3 we know that $G(x, 0, E_x) > B_L$ for all $x \geq 0$. Hence $e_x = 0$ and $\tau_0(E_0, B_0) = 0$. Similarly, if $B_H = (1-\alpha)D(E_0) + \alpha D'(E_0)E_0$, then $G(0, E_0, E_0) = B_H$. Hence if $B > B_H$ we have $G(0, E_0, E_0) < B$ and again by lemma 3 this holds for all $x \geq 0$ and thus $\tau_F = 1$ and $e_x = E_0$ (this last part in effect requires solving the same differential equation as we did in lemma 5, which I omit).

Moreover, note that if $B < B_H$ then we have that $G(0, E_0, E_0) > B$ and thus (by continuity of E_x and G) we have that $G(x, \frac{E_x}{1-x}, E_x) > B$ for all sufficiently small x. Therefore, $\tau_F < 1$. Similarly, if $B > B_L$ we have that $\tau_0 < 1$.

It is clear by lemma 3 that if $\tau_0 > 0$ then $\tau_F = 0$ and if $\tau_F > 0$ then $\tau_0 = 0$. Let $B_{C,0} = \liminf\{B : \tau_0(E_0, B) = 0\}$ – roughly the smallest B for which there is some work done at all times x. Then because τ_0 is decreasing in B_0 by lemma 6, we know that if $B < B_{C,0}$ then $\tau_0(E_0, B) > 0$, since if $\tau_0(E_0, B) = 0$, then $\tau_0(E_0, B') = 0$ for all $B' \geq B$, contradicting the definition of $B_{C,0}$. Similarly we can define $B_{C,F} = \limsup\{B : \tau_F(E_0, B) = 0\}$ and show that if $B > B_{C,F}$ then $\tau_F > 0$.

To finish the proof, we need to show that $B_{C,F} = B_{C,0}$. Notice that if $B_0 \in [B_{C,0}, B_{C,F}]$ we have that $\tau_0 = 0$ and $\tau_F = 0$. Therefore $G(x, e_x, E_x(E_0, B_0)) = B$ for all $x < 1$. Suppose that $B_{C,0} < B_{C,F}$.[22] Since $G(x, e_{x,0}, E_{x,0}) = B_{C,0} < B_{C,F} = G(x, e_{x,F}, E_{x,F})$ for all x, we must have that $e_{x,F} > e_{x,0}$ or $E_{x,F} > E_{x,0}$ for every x. By continuity of E_x in x and G in E, we can pick $\varepsilon > 0$ such that $G(x, e_{x,0}, E_{x,F})$ is arbitrarily close to $G(x, e_{x,0}, E_{x,0}) = B_{C,0}$ so that $e_{x,F} > e_{x,0}$ for all $x < \varepsilon$. Thus $E_{x,F} < E_{x,0}$ and we can show that $e_{x,F} > e_{x,0}$ for all x. Suppose not, then we must have that

[22] We cannot have $B_{C,0} > B_{C,F}$ since then $\tau_F > 0$ and $\tau_0 >$ for all $x \in (B_{C,F}, B_{C,0}$, but both cannot happen together.

$E_{x,F} > E_{x,0}$ for some x and therefore there exists a smallest $x^* > \varepsilon$ such that $E_{x^*,F} = E_{x^*,0}$. But $e_{x,F} > e_{x,0}$ for all $x < x^*$, therefore $E_{x^*,F} < E_{x^*,0}$, which is a contradiction.

Thus we have shown that $E_{x,F} < E_{x,0}$ and that $e_{x,F} > e_{x,0}$ for all $x > 0$. Let $\delta = E_{\frac{1}{2},0} - E_{\frac{1}{2},F} > 0$, then $E_{x,0} - E_{x,F} \geq \delta$ for $x > \frac{1}{2}$ and therefore $E_{x,0} \geq \delta > 0$ for all x. Therefore $D(\frac{E_{x,0}}{1-x})(1-x) \geq D(\frac{\delta}{1-x})\frac{1-x}{\delta}\delta \to \infty$ as $x \to 1$ by lemma 7. But this means that $G(x, 0, E_{x,0}) \to \infty$ and therefore that $G(x, 0, E_{x,0}) > B$ as $x \to 1$, so that $\tau_0 > 0$. Therefore, we cannot have that $B_{C,0} < B_{C,F}$ and we are done. $\square$

Here is the lemma I referred to at the end of the previous proof.

Lemma 7. *Let D be convex with $D'(e) \to \infty$ as $e \to \infty$. Then $\forall K > 0$, $\exists E$ s.t. $D(e) > K \cdot e$ $\forall e > E$. That is, $D(e)/e \to \infty$ as $e \to \infty$.*

Proof. Since $D'(e) \to \infty$, pick E s.t. $D'(\frac{E}{2}) > 2 \cdot K$. Then for $e > E$

$$D(e) = \int_0^e D'(s)ds \geq \int_{E/2}^e D'(s)ds \geq \int_{E/2}^E 2 \cdot K ds \geq \frac{e}{2} 2 \cdot K = e \cdot K$$

$\square$

Now let us show that the utility is continuous and decreasing on (B_L, B_C) and continuous and increasing on (B_C, B_H).

Lemma 8. *The utility $u_0(E_0, B_0) := -\int_0^1 D(e_x)dx$ is continuous and decreasing on $(B_L(E_0), B_C(E_0))$ and the utility $u_F(E_0, B_0) := B - \int_0^1 D(e_x)dx$ is continuous and increasing on $(B_C(E_0), B_H(E_0))$.*

Proof. Notice that when $B \in (B_L, B_C)$ then we know that $\tau_0 \in (0, 1)$ and the task is not completed, hence the definition of the utility as u_0 is correct. Moreover $u_0 = \int_0^{1-\tau_0} D(e_x)dx$. We can show that τ_0 and E_x are continuous and decreasing in B_0. Picking $B_0 < B_0'$, we therefore have that $\tau_0' < \tau_0$ and that for $x \leq 1 - \tau_0$ we have $G(x, e_x, E_x) = B_0 < B_0' = G(x, e_x', E_x')$. Since $E_x' \leq E_x$ we therefore have that $e_x' > e_x$ and therefore $u_0' > \int_0^{1-\tau_0} D(e_x')dx > \int_0^{1-\tau_0} D(e_x)dx = u_0$. Moreover, if B_0' is close to B_0 then E_x is close to E_x' by Lipschitz continuity and therefore e_x' and e_x are close together, since e_x is Lipschitz continuous in all the parameters as well (I haven't shown this in detail, but this is where I use the condition $D'(0) > 0$). Therefore the u_0' and u_0 are close.

Now suppose B_0, $B_0' \in (B_C, B_H)$ then $\tau_F \in (0, 1)$. Let $B_0 < B_0'$. We can show in a similar way as before that $\tau_F' > \tau_F$ and that $e_x' > e_x$ for $x \leq 1 - \tau_0'$. Then notice that $\int_0^1 e_x = E_0 = \int_0^1 e_x'$. Let $F(e) := \mathbb{P}(e_x \leq e) = \int_0^1 \mathbb{1}(e_x \leq e)dx$ and $G(e) := \mathbb{P}(e_x' \leq e) = \int_0^1 \mathbb{1}(e_x' \leq e)dx$, where the interpretation as probabilities is to help intuition, although it can be made formal by drawing x uniformly from $[0, 1)$. We want to show that $\int_0^1 D(e)dF(e) > \int_0^1 D(e)dG(e)$. By strict convexity of $D(\cdot)$, this holds if $F(\cdot)$ is a mean-preserving spread of $G(\cdot)$. Let $\bar{e}_G = e_{1-\tau_F'}$, be the effort the person exerts under $G(\cdot)$ once they work fully, with B_0'. Then if $e < \bar{e}$, $G(e) < F(e)$, since $e_x' > e_x$ for all $x \leq 1 - \tau_0')$, which are the only e that can below $\bar{e}$ under $G(\cdot)$, while $F(\cdot)$ can get contributions from $e > \bar{e}_G$. However $G(\bar{e}) = 1$ for $e > \bar{e}_G$, while $F(\bar{e}) \geq 1$, we have that $F(e) \geq G(e)$ for $e \geq \bar{e}$. Therefore F is a mean-preserving spread of G, moving effort from above $\bar{e}$ to below, and thus the disutility for e_x is higher than for $e_x^{'}$.[23] Continuity follows again by noting that, until time $1-\tau_0$, e_x is Lipschitz continuous in all parameters, and thereafter it is constant. Therefore the utility is Lipschitz continuous. $\square$

I will need the following two lemmas to prove the second part of the proposition.

Lemma 9. *Let D be convex and such that $D'(e) \to \infty$ as $e \to \infty$. Fix B and $\varepsilon > 0$. Let e_ε be s.t.*

$$D(e_\varepsilon) \cdot \varepsilon = B \tag{11}$$

Then $e_\varepsilon \cdot \varepsilon \to 0$ as $\varepsilon \to 0$.

Proof. First note that as ε goes to 0, e_ε goes to ∞, since if it was bounded, then $D(e_\varepsilon) \cdot \varepsilon$ would go to 0. By lemma 7, we know that $\frac{D(e_\varepsilon)}{e_\varepsilon} \to \infty$. Dividing both sides of equation 11 by $\varepsilon \cdot e_\varepsilon$ yields

$$D(e_\varepsilon)/e_\varepsilon = \frac{B}{e_\varepsilon \cdot \varepsilon} \iff e_\varepsilon \cdot \varepsilon = \frac{B}{D(e_\varepsilon)/e_\varepsilon} \to 0$$

which proves the claim. $\square$

Lemma 10. *Take the continuous time problem with effort $E_0 > 0$. Then for every $\varepsilon > 0$ there exists B^* s.t. with $B_0 = B^*$, the following holds at time $1-\varepsilon$.*

$$D\left(\frac{E_{1-\varepsilon}}{\varepsilon}\right) \cdot \varepsilon = B^* \tag{12}$$

Proof. Consider the function $F(B_0) := B_0 - D(\frac{E_x}{1-x})(1-x)$. Clearly $F(0) < 0$. Morevoer, as $B_0 \to \infty$, the task is done efficiently and eventually worth doing, say for $B_0 = \bar{B}$ this occurs. Then we have $\frac{E_x}{1-x} = E_0$, with $D(E_0) < \bar{B}$. Thus $F(\bar{B}) = \bar{B} - D(E_0)(1-x) > 0$. We know from lemma 2 that $E_x(B_0)$ is a continuous and decreasing function in B_0. Hence so is $F(\cdot)$, therefore there is some $B^* \in (0, \bar{B})$ s.t. $F(B^*) = 0$, i.e.

$$B^* = D(\frac{E_x}{1-x})(1-x) \implies B^* = D(\frac{E_{1-\varepsilon}}{\varepsilon})\varepsilon$$

for $\varepsilon = 1 - x > 0$. $\square$

Here is the proof of the second part of proposition 4 in the continuous-time setting.

Proposition 10. *Suppose there is some $d > 0$ s.t. $D''(e) > d$ for all e and $D'(E) \to \infty$ as $E \to \infty$. Then $\lim_{B_0 \to B_C^-} u_0(E_0, B_0) \leq -D(E_0)$.*

Proof. Since τ_0 is continuous and decreasing on $(B_L(E_0), B_H(E_0))$, and since τ_0 can be 0 and 1, we know that for every $\tau \in (0,1)$ there is some $B_0 \in (B_L(E_0), B_H(E_0))$ such that $\tau_0(E_0, B_0) = \tau$. Notice that at time τ_0 we have that $G(1-\tau_0, 0, \frac{E_{1-\tau_0}}{\tau_0}) = B_0$. Therefore $(1-\alpha)D(\frac{E_{1-\tau_0}}{\tau_0})\tau_0 + \alpha D'(0)E_{1-\tau_0} =$

[23] A rigorous proof of this would require to show that $e_x^{'} < \bar{e}_G$, so that the final effort exerted is the highest effort ever exerted.

B_0. As $\tau_0 \to 0$, we must therefore have that $E_{1-\tau_0} \to 0$, since otherwise $G \to \infty$. But this means that almost all the work gets done before time $1-\tau_0$ for which the least disutility is $D(E_0-\varepsilon) > D(E_0)-\delta$ for sufficiently small ε (i.e. τ_0 sufficiently close to 1). Therefore the disutility is at least $D(E_0) - \delta$ for arbitrary δ. Hence the result holds. □

The propositions then follow if we can show that in the limit, the discrete time solution approaches the continuous time solution.

Multi-Day All-or-Nothing Tasks: Continuous to Discrete Time

With the following lemma, we are done, since it shows that as T goes to infinity, everything converges to the quantities in the continuous-time problem, for which we have shown that the statements in proposition 4 and in proposition **??** hold.

Lemma 11. *If* $B_0 \in (B_L(E_0), B_C(E_0))$*, then* $\lim_{T\to\infty} \tau_0^D(E_0, B_0, T) = \tau_0(E_0, B_0)$ *and* $\lim_{T\to\infty} u^D(E_0, B_0, T) = u(E_0, B_0)$*. If* $B_0 \in (B_C(E_0), B_H(E_0))$*, then* $\lim_{T\to\infty} \tau_F^D(E_0, B_0, T) = \tau_F(E_0, B_0)$ *and* $\lim_{T\to\infty} u^D(E_0, B_0, T) = u(E_0, B_0)$*.*

Proof. When $B_0 \in (B_L(E_0), B_C(E_0))$, we want to show that $\forall\delta > 0$, $\exists T^* > 0$ such that $\forall T > T^*$ we have both of the following

$$|\tau_0^D - \tau_0| < \delta$$
$$|u_0^D - u_0| < \delta$$

where $\tau_0^D := \tau_0^D(E_0, B_0, T)$ and $\tau_0 := \tau_0(E_0, B_0)$, and $u_0^D := u^D(E_0, B_0, T)$ and $u_0 := u(E_0, B_0)$. I will show this by finding large N and T^* such that for $\tau_0^- := \tau_0(E_0 - \frac{1}{N}, B_0)$ and $\tau_0^+ := \tau_0(E_0 + \frac{1}{N}, B_0)$ we get $\tau_0^D \in [\tau_0^-, \tau_0^+]$ with $|\tau_0^- - \tau_0^+| < \delta$ and u_0, $u_0^D \in [u_0^-, u_0^+]$ and $|u_0^- - u_0^+| < \delta$, which will prove the claim.

First, by lemma 6, we know that τ_0 is continuous and decreasing and u_0 is continuous and increasing on $[0, B_C(E_0))$, thus (since $B_0 < B_C(E_0)$ given that the task is not completed) we can find a neighborhood $\mathcal{E}$ of E_0 such that τ_0 and u_0 are continuous and increasing in E_0. Pick N_1 large enough so that $E_0 - \frac{1}{N}$ and $E_0 + \frac{1}{N} \in \mathcal{E}$. τ_0 and u_0 are continuous in $E \in \mathcal{E}$, thus we can choose N larger than N_1 large enough such that $|\tau_0^+ - \tau_0^-| < \delta$ and $|u_0^+ - u_0^-| < \delta$ and so that $|\tau_0^- - \tau_0| < \frac{1}{2}\tau_0$. Since τ_0 is decreasing in E, we have that $\tau_0 \in [\tau_0^+, \tau_0^-]$ and since u_0 is increasing in E we have that $u_0 \in [u_0^-, u_0^+]$.

To prove the remainder, pick T^* large enough so that $\frac{E_0+1}{\frac{1}{2}\tau_0^+ T^*} < \frac{1}{N}$ and consider any $T > T^*$ and such that $\frac{1}{T} < \frac{1}{2}\tau_0$. Let $x_t = \frac{t-1}{T}$ for $t \in \{1, ..., T\}$. First, let us show that if $x_t \leq 1 - \frac{1}{2}\tau_0$, then

$$E_{x_t}^- \leq E_{x_t}^D - \frac{1}{N} \implies G^D(x_t, s, E_{x_t}^D) > G(x, s, E_x^-) \forall x \in [x_t, x_{t+1}]$$
$$E_{x_t}^D + \frac{1}{N} \leq E_{x_t}^+ \implies G^D(x_t, s, E_{x_t}^D) < G(x, s, E_x^+) \forall x \in [x_t, x_{t+1}]$$

We have the following:

$$
\begin{aligned}
G(x, s, E_x^-) &\leq G(x_{t+1}, s, E_x^-) \text{ since } G \text{ increases in } x && (13)\\
&\leq G(x_{t+1}, s, E_{x_t}^-) \text{ since } G \text{ increases in } E \text{ which decreases in } x && (14)\\
&= (1-\alpha)D\left(\frac{E_{x_t}^-}{1-x_{t+1}}\right)(1-x_{t+1}) + \alpha D'(s)E_{x_t}^- && (15)
\end{aligned}
$$

Now note the following:

$$
\begin{aligned}
\frac{E_{x_t}^-}{1-x_{t+1}} &= \frac{E_{x_t}^- \frac{1-x_t}{1-x_{t+1}}}{1-x_t} = \frac{E_{x_t}^-(1+\frac{x_{t+1}-x_t}{1-x_{t+1}})}{1-x_t}\\
&= \frac{E_{x_t}^- + \frac{E_{x_t}^-}{T(1-x_{t+1})}}{1-x_t}, \text{ since } x_{t+1} - x_t = \frac{1}{T}\\
&\leq \frac{E_{x_t}^- + \frac{E_{x_t}^-}{T\tau_0\frac{1}{2}}}{1-x_t} \text{ since } 1 - x_{t+1} \geq \frac{1}{2}\tau_0\\
&\leq \frac{E_{x_t}^- + \frac{E_0+1}{T\tau_0\frac{1}{2}}}{1-x_t} \text{ since } E_{x_t}^- \leq E_0^- \leq E_0 + \frac{1}{N} \leq E_0 + 1\\
&< \frac{E_{x_t}^- + \frac{1}{N}}{1-x_t} \text{ since } T > T^* \text{ and by how } T^* \text{ is chosen}\\
&\leq \frac{E_{x_t}^D}{1-x_t} \text{ by the assumption we made}
\end{aligned}
$$

Plugging this into equation (15), we have:

$$
G(x, s, E_x^-) = (1-\alpha)D\left(\frac{E_{x_t}^D}{1-x_t}\right)(1-x_{t+1}) + \alpha D'(s)E_{x_t}^- \tag{16}
$$

Therefore we have that $\forall s \leq \frac{E_{x_t}^D}{1-x_t}$

$$
\begin{aligned}
(1-x_{t+1})D\left(\frac{E_{x_t}^D}{1-x_t}\right) &= (1-x_t)D\left(\frac{E_{x_t}^D}{1-x_t}\right) - \frac{1}{T}D\left(\frac{E_{x_t}^D}{1-x_t}\right)\\
&\leq (1-x_t)D\left(\frac{E_{x_t}^D}{1-x_t}\right) - \frac{1}{T}D(s)
\end{aligned}
$$

which we can plug into equation (16):

$$
G(x, s, E_x^-) = (1-\alpha)\left(D\left(\frac{E_{x_t}^D}{1-x_t}\right)(1-x_t) - \frac{1}{T}D(s)\right) + \alpha D'(s)E_{x_t}^- \tag{17}
$$

and that

$$
\begin{aligned}
E^-_{x_t} \leq E^D_{x_t} - \frac{1}{N} &< E^D_{x_t} - \frac{E_0+1}{T\frac{1}{2}\tau_0}, \text{ since } \frac{E_0+1}{\frac{1}{2}T\tau_0^+}, T^* \geq T, \tau_0 \geq \tau_0^+ \\
&< E^D_{x_t} - \frac{E^D_{x_t}}{T\frac{1}{2}\tau_0}, \text{ since } \frac{1}{2}\tau_0 \leq 1 - x_t \\
&< E^D_{x_t} - \frac{E^D_{x_t}}{T(1-x_t)}, \text{ since } E_0 + 1 > E^t_{x_t} \\
&\leq E^D_{x_t} - \frac{s}{T}
\end{aligned}
$$

which finally when plugging it into (17), gives us the result we want:

$$
\begin{aligned}
G(x, s, E^-_x) &< (1-\alpha)\left(D(\frac{E^D_{x_t}}{1-x_t})(1-x_t) - \frac{1}{T}D(s)\right) + \alpha D'(s)\left(E^D_{x_t} - \frac{s}{T}\right) \\
&= G^D(x_t, s, E^D_{x_t})
\end{aligned}
$$

Next we have:

$$
\begin{aligned}
G(x, s, E^+_x) &\geq G(x_t, s, E^+_x) \text{ because } G \text{ is increasing in } x && (18) \\
&\geq G(x_t, s, E^+_{x_{t+1}}) \text{ because } G \text{ is increasing in } E \text{ and } E^+_{x_{t+1}} \leq E^+_x && (19)
\end{aligned}
$$

By lemma 5, we have

$$
\frac{E^+_{x_{t+1}}}{1-x_{t+1}} \geq \frac{E^+_{x_t}}{1-x_t} \implies E^+_{x_{t+1}} \geq E^+_{x_t}\frac{1-x_{t+1}}{1-x_t} = E^+_{x_t}\left(1 - \frac{1}{T(1-x_t)}\right)
$$

Thus

$$
\begin{aligned}
E^+_{x_{t+1}} &\geq E^+_{x_t} - \frac{E^+_{x_t}}{T(1-x_t)} \\
&\geq E^D_{x_t} + \frac{1}{N} - \frac{E^+_{x_t}}{T(1-x_t)}, \text{ since } E^+_{x_t} \geq E^D_{x_t} + \frac{1}{N} \\
&\geq E^D_{x_t} + \frac{1}{N} - \frac{E^+_0}{T\frac{1}{2}\tau_0}, \text{ since } E^+_{x_t} \leq E^+_0 \text{ and } 1 - x_t > \frac{1}{2}\tau_0 \\
&\geq E^D_{x_t} + \frac{1}{N} - \frac{E_0+1}{T\frac{1}{2}\tau_0}, \text{ since } E^+_0 = E_0 + \frac{1}{N} \leq E_0 + 1 \\
&> E^D_{x_t}, \text{ since } \frac{E_0+1}{T\frac{1}{2}\tau_0} < \frac{1}{N}
\end{aligned}
$$

Plugging this into equation (19), we get

$$G(x,s,E_x^+) > G(x_t,s,E_{x_t}^D) \geq G^D(x_t,s,E_{x_t}^D)$$

which proves the second of the two statements.

Let P_t^- be the statement that $E_{x_{t'}}^- \leq E_{x_{t'}}^D - \frac{1}{N}$ for all $t' \leq t$ and that $e_x^D \leq e_x^-$ for all $x < x_t$. By construction, P_1 holds, since $x_1 = 0$, and we have $E_0^- = E_0 - \frac{1}{N} < E_0^D = E_0 < E_0 + \frac{1}{N} = E_0^+$. Suppose P_t holds. Then if $x_{t+1} \leq 1 - \frac{1}{2}\tau_0$, we have that $e_{x_t}^D \leq e_x^-$ and therefore that P_{t+1} holds. First, note that $G(x, e_x^-, E_x^-) \geq B$ for all $x \in [x_t, x_{t+1}]$, since if $G(x, \frac{E_x^-}{1-x}, E_x^-) < B$, then $\tau_0^- = 0$, which we ruled out by choosing N sufficiently large. We can use the bounds between G and G^D just proved, thus we have $B \leq G(x, e_x^-, E_x^-) < G^D(x_t, e_x^-, E_{x_t}^D)$. This implies that $e_{x_t}^D \leq e_x^-$, since if it was strictly larger, then we'd have $B < G^D(x_t, e_x^D, E_{x_t}^D)$, with $e_x^D > 0$, which means the person works past the point where they find the problem worth doing – which is not possible. Therefore $E_{x_{t+1}}^D = E_{x_t}^D - e_{x_t}^D \geq E_{x_t}^- + \frac{1}{N} - e_x^- = E_{x_{t+1}}^- + \frac{1}{N}$. Therefore P_t holds for all t such that $x_t \leq 1 - \frac{1}{2}\tau_0$.

Now note that because of how we picked N and T, we have that $0 < \tau_0 - \tau_0^- < \frac{1}{2}\tau_0$ and that $\frac{1}{T} < \frac{1}{2}\tau_0$. Therefore we have that $\frac{1}{2}\tau_0 < \tau_0^- < \tau_0$, thus $1 - \tau_0 < 1 - \tau_0^- < 1 - \frac{1}{2}\tau_0$ and finally $(1 - \frac{1}{2}\tau_0) - (1 - \tau_0^-) = (1 - \frac{1}{2}\tau_0) - (1 - \tau_0) + (1 - \tau_0) - (1 - \tau_0^-) = \frac{1}{2}\tau_0 + \tau_0^- - \tau_0 > \frac{1}{2}\tau_0 > \frac{1}{T}$. Let t^* be the largest t such that $x_t \leq 1 - \tau_0^-$. Then $x_{t^*+1} = x_{t^*} + \frac{1}{T} \leq 1 - \tau_0^- + \frac{1}{T} < 1 - \frac{1}{2}\tau_0$, and therefore P_{t^*} holds and P_{t^*+1} holds. Therefore $e_{x_{t^*}}^D \leq e_x^-$ for all $x \in [x_{t^*}, x_{t^*+1}]$, which means that $e_{x_t^*} = 0$ since $e_{x_{t^*+1}}^- = 0$. This proves that $\tau_0^D \geq \tau_0^-$.

A similar argument defininig P_t^+ as the statement that holds that $E_{x_{t'}}^+ \geq E_{x_{t'}}^D + \frac{1}{N}$ for all $t' \leq t$ and that $e_x^D \geq e_x^+$ for all $x < x_t$ can be made to show that P_t^+ holds for all t with $x_t \leq 1 - \frac{1}{2}\tau_0$ and therefore $\tau_0^D \leq \tau_0^+$. Moreover, since the effort is always in between, and the task is never completed, it is clear that the disutility u_0^D lies in between u^- and u^+.

This proves the first half of the proposition, when $B_0 \in (B_L(E_0), B_C(E_0))$.

Now let us look at the case when $B_0 \in (B_C(E_0), B_H(E_0))$. The proof is identical if we replace τ_0 by τ_F, until we get to the final step regarding property P_t^- and property P_t^+.

Let P_t^+ be the statement that $E_{x_{t'}}^+ \geq E_{x_{t'}}^D + \frac{1}{N}$ for all $t' \leq t$ and that $e_x^D \geq e_x^-$ for all $x < x_t$. By construction, P_1 holds. Suppose P_t holds. Then if $x_t \leq 1 - \tau_F^+$, we have that $x_{t+1} < 1 - \frac{1}{2}\tau_F$ by our choice of N and T (this uses a similar argument as in the τ_0 case). Therefore we know that $G(x,s,E_x^+) \geq G^D(x_t,s,E_{x_t}^D)$ $\forall x \in [x_t, x_{t+1}]$. We have that $B = G(x, e_x^+, E_x)$ (since we know that the person works partially until time $1 - \tau_F^+$) and thus $B > G^D(x_t, e_x^+, E_{x_t}^D)$. Therefore we have that $e_{x_t}^D \geq e_x^+$ or $e_{x_t}^D = \frac{E_{x_t}^D}{1-x_t}$, i.e. work is done efficiently from then onwards. Thus, either we have that P_{t+1} holds or that $\tau_F^D \geq \tau_F^+$. Suppose that t^* is the largest t for which P_t holds. Then if $x_{t^*} \leq 1 - \tau_F^+$ we know that either P_{t^*+1} holds or that $\tau_F^D \geq \tau_F^+$. Thus $\tau_F^D \geq \tau_F^+$ since by the definition of t^*, P_{t^*} cannot hold. If we have that $x_{t^*} > 1 - \tau_F^+$, then we know that P_{t^*} holds, and thus $e_{x_{t^*}}^D \geq e_x^-$ for all $x < x_{t^*}$, i.e. for all $x \leq 1 - \tau_F^+$ as well. But when $x_t > 1 - \tau_F^+$, the person efficiently completes the work, thus $e_{\tau_F^+} = e_x = \frac{E_{\tau_F^+}^+}{\tau_F^+}$, this means that $e_{\tau_F^+}^D \geq \frac{E_{\tau_F^+}^+}{\tau_F^+} > \frac{E_{\tau_F^+}^D}{\tau_F^+}$, which implies that the person works more than is efficient, which is a contradiction. Thus $x_{t^*} \leq 1 - \tau_F^+$ and $\tau_F^D \geq \tau_F^+$, with P_t holding for all $x_t \leq 1 - \tau_F^D$.

A similar argument establishes that $\tau_F^D \leq \tau_F^-$ and that $e_x^- \geq e_x^D$ for all $x \leq 1 - \tau_F^-$. Then we can apply lemma 8 which shows that in this case $u_F^+ \leq u_F^D \leq u_F^-$. This completes the proof. □

A.2.2 Proofs of Results on Multi-Day Multi-Tasking

Proof of proposition 5.

Proof. Let $\tilde{f}_1^*(s)$ be the amount of effort the person plans to put into the short-term task on day 1 when they have worked for s hours so far and not yet switched. Let $\tilde{l}_1^*(s)$ be the amount of effort planned to put into the long-term task on day 1 after having worked for s hours. Let $\tilde{o}_1^*(s)$ be the amount of effort planned to put into the second task on day 1 when we have a one-day problem only – i.e. the setup is like in section 3. Notice that since disutility and benefits are equal from work across all days, the person always plans to exert the same effort today and on all future days – as long as they haven't committed by having exerted the effort already.

Then until switching happens on day 1, the person plans effort based on the following FOCs:

$$\tilde{D}'(\tilde{f}_1^*(s) + \tilde{l}_1^*(s)|s) = B_f'(\tilde{f}_1^*(s)) = B_l'(\tilde{l}_1^*(s))$$

and the same holds for the one-day version with $\tilde{l}_1^*(s)$ replaced by $\tilde{o}_1^*(s)$. Then the person switches and hence determines the amount worked on the first task when s is equal to $\tilde{f}_1^*$:

$$\tilde{D}'(\tilde{f}_1^* + \tilde{l}_1^*(\tilde{f}_1^*)|\tilde{f}_1^*) = B_f'(\tilde{f}_1^*) = B_l'(\tilde{l}_1^*(\tilde{f}_1^*))$$

Since this is exactly the same condition as for the one-day problem, we see that $\tilde{f}_1^*$ and hence the switching time is the same as in the one-day problem.

The FOC determining when the person stops in the one-day problem then looks like this (see also the proof of proposition 2), where it is worth noting that the marginal disutility is perceived correctly since the person is currently experiencing the marginal disutility (rather than predicting it):

$$D'(\tilde{f}_1^* + \tilde{o}_1^*) = B_l'(\tilde{o}_1^*)$$

Note that the marginal disutility is not equal to the marginal benefits from the first task, since those benefits were determined at the time of switching, but no longer are equal to the current marginal disutility.

For the multi-day problem however, the person ensures that they work the same amount in total across all days, but while their plans for future work on the short-term and long-term tasks need not be the same are constant for all future days, these plans are not equal to today's effort:

$$D'(\tilde{f}_1^* + \tilde{l}_1^*) = D'(\tilde{f}_{2|1}^* + \tilde{l}_{2|1}^*) = B_f'(\tilde{f}_{2|1}^*) = B_l'(\frac{\tilde{l}_1^* + (T-1)\cdot \tilde{l}_{2|1}^*}{T})$$

where $\tilde{f}_{2|1}^*$ indicates the effort the person plans at the end of day 1 on exerting on the first task on day 2 – and similarly for $\tilde{l}_{2|1}^*$.

Step 1: I will show that we have $\tilde{f}_1^* + \tilde{l}_1^* < \tilde{f}_1^* + \tilde{o}_1$ – so that the person works less in total on the first day of the multi-day problem than they do for the one-day problem.

Suppose not, so that $\tilde{f}_1^* + \tilde{l}_1^* \geq \tilde{f}_1^* + \tilde{o}_1$. Then we have:

$$
\begin{aligned}
&D'(\tilde{f}_1^* + \tilde{l}_1^*) = D'(\tilde{f}_{2|1}^* + \tilde{l}_{2|1}^*) = B_f'(\tilde{f}_{2|1}^*) = B_l'(\frac{\tilde{l}_1^* + (T-1)\cdot \tilde{l}_{2|1}^*}{T}) \\
\geq &D'(\tilde{f}_1^* + \tilde{o}_1^*) = B_l'(\tilde{o}_1^*) \\
> &B_l'(\tilde{o}_1^*(\tilde{f}_1^*)) = B_f'(\tilde{f}_1^*)
\end{aligned}
$$

where we proved the final inequality in proposition 2.

But since $B_f(\cdot)$ is strictly concave, we have that

$$
\tilde{f}_1^* > \tilde{f}_{2|1}^* \tag{20}
$$

and since $B_l(\cdot)$ is strictly concave, we have that

$$
\frac{\tilde{l}_1^* + (T-1)\cdot \tilde{l}_{2|1}^*}{T} < \tilde{o}_1^* \tag{21}
$$

However, clearly since $\tilde{f}_1^* + \tilde{l}_1^* \geq \tilde{f}_1^* + \tilde{o}_1^*$, we have that $\tilde{l}_1^* \geq \tilde{o}_1^*$. But from the FOCs, we have that $\tilde{f}_{2|1}^* + \tilde{l}_{2|1}^* = \tilde{f}_1^* + \tilde{l}_1^*$. Together with equation 20, this implies that $\tilde{l}_{2|1}^* > \tilde{l}_1^* \geq \tilde{o}_1^*$. Therefore $\frac{\tilde{l}_1^* + (T-1)\cdot \tilde{l}_{2|1}^*}{T} > \tilde{o}_1^*$, which directly contradicts equation **??**. This contradiction proves step 1.

Step 2: We will now prove the following 4 properties:

1. Actual total effort spent on both tasks, $\tilde{f}_t^* + \tilde{l}_t^*$, strictly increases over time
2. Actual effort spent on the first task, $\tilde{f}_t^*$, strictly decreases over time
3. Actual effort spent on the long-term task, $\tilde{l}_t^*$, strictly increases over time
4. Average effort spend on the first task , is strictly lower than the effort spend on the first task in the one-day case (which is equal by step 1 to time spent on the first day on the first task) for all but the first day: $\frac{1}{T}\sum_{i=1}^{t} \tilde{f}_i^* < \tilde{f}_1^* \forall t > 1$

Notice that the third claim directly follows from the first two claims, since if effort on the first task decreases and total effort increases, this implies that effort on the second (long-term) task must increase.

The final claim immediately follows from the strict decrease in effort spent on the first task.

Property 1 holds by applying lemma 1 from section 6 to $\tilde{U}(\boldsymbol{f}, \boldsymbol{l}) = B(\boldsymbol{f}, \boldsymbol{l}) - (1-\alpha)\cdot \sum D(f_t + l_t) + \alpha \cdot (-D'(s)) \cdot \sum (f_t + l_t)$, which applied to this case says that as we strictly increase $-D'(s)$, the maximizing choice of $\boldsymbol{f}$ and $\boldsymbol{l}$ will strictly increase $\sum (f_t + l_t)$. Thus as we strictly decrease $D'(s)$, total planned effort strictly increases: the more rested the person is, the more they plan on working.

Now suppose that it was not true that total effort increases. Then it decreases or stays the same, hence the person is switching at a time when the amount of work done up to that point, s, is lower than the total work done on day t. Hence, between the end of day t until the moment on day $t+1$ where they decide to switch to the long-term task the FOCs are exactly identical except for a strict decrease in $D'(s)$, which implies that they must be strictly working less, which is a contradiction, proving the property.

We can prove property 2 as follows. On day t, the person switches at $\tilde{f}_t^*$. At this time, they plan on working $\tilde{l}_t^*(\tilde{f}_t^*)$ on the long-term task on day t; however they end up working less on it, namely $\tilde{l}_t^*$, which we can show by an identical argument as we made under step 1 to show that work on day 1 is less than planned at time of switching.

Thus on day $t+1$, suppose contrary to property 2 that the person does not yet switch earlier than on day t. We know that if they had worked as much as they had planned on day t, then the same first order condition would still hold at the same switching time, since the person is equally tired at that point, did all the past actions according to plan, and perceives all benefits and disutilities equally. However, they did not work as planned; rather they worked strictly less on day t than they anticipated. Due to the strict concavity of $B_l(\cdot)$, this implies that the marginal benefits from working on the long-term task are (correctly) perceived strictly larger at this time, while the marginal benefits from the short-term task are the same as yesterday – but this clearly means they shouldn't have worked this long on the short-term task, again a contradiction.

This proves all the properties.

Step 3: The person spends less effort than optimal on the long-term task for every time t, i.e. $\sum_{i=1}^{t} \tilde{l}_t^* < t \cdot l^* \forall t$.

We proved the statement for $t = 1$ via step 1, showing that the person exerts less effort than in the one-day multi-tasking case, which is itself below the optimum. Suppose we proved the statement for all $\tau \leq t$. Then it must hold for $t + 1$ too.

To show this, consider the following continuation problem: Let $\tilde{L}_t$ be the total amount of effort exerted by the person so far. Then replace the benefit $B_l(\cdot)$ of the long-term task by the new benefit $\hat{B}_l(e) = B_l(e \cdot \frac{T-t}{T} + \frac{L}{T})$. In that case, letting $e = \frac{e_{t+1}+...+e_T}{T-t}$ is the average effort exerted over the last final days, and we have

$$
\begin{aligned}
\hat{B}_l(e) &= B_l(e \cdot \frac{T-t}{T} + \frac{L}{T}) \\
&= B_l(\frac{e_{t+1} + e_T}{T} + \frac{e_1 + ... + e_t}{T}) \\
&= B_l(\frac{e_1 + ... + e_T}{T})
\end{aligned}
$$

gives the true benefit from this average effort over the last $T - t$ days. But, the problem we now consider can be treated as a problem with no past mistakes, so that day $t + 1$ is equal to day 1 of the new problem with benefits $\hat{B}_l(\cdot)$, hence the behavior is identical for all agents.

Applying step 1 to this new problem, we therefore know that $\tilde{l}_1^* < \hat{l}_1^*$, that is the biased agent works less than is optimal in this continuation problem. Going back to the original problem, it is clear that an unbiased agent who on day $t+1$ has fallen behind the optimal schedule will not be able to fully catch up even by the final day, it implies that they also haven't caught up by day $t+1$. Hence $(t+1) \cdot l^* > L + \hat{l}_1^* > L + \tilde{l}_1^* = \sum_{i=1}^{t+1} \tilde{l}_i^*$, proving the claim.

This completes the proof. $\square$

A.3 Proofs for Section 5

Lemma 12. *Let $U_a(\boldsymbol{e}) = X(\boldsymbol{e}) + a \cdot Y(\boldsymbol{e})$, with X and Y continuous (real-valued) functions of the vector $\boldsymbol{e}$, and $a \in \mathbb{R}$. Then, for all a, $\arg\max_{e \in \mathcal{E}} U_a(\boldsymbol{e})$ is not empty when $\mathcal{E}$ is a compact set. Let $\boldsymbol{e}(a) \in \arg\max_{e \in \mathcal{E}} U_a(\boldsymbol{e})$. If $a_H > a_L \geq 0$, then $X(\boldsymbol{e}(a_H)) \leq X(\boldsymbol{e}(a_L))$ and $Y(\boldsymbol{e}(a_H)) \geq Y(\boldsymbol{e}(a_L))$.*

Proof. By compactness of $\mathcal{E}$ and continuity of X and Y, the maximimum is achieved in $\mathcal{E}$ we can find $\boldsymbol{e}(a)$ as stated. Denote $X(\boldsymbol{e}(a_i))$ by X_i, $Y(\boldsymbol{e}(a_i))$ by Y_i for $i \in \{H, L\}$. Since $\boldsymbol{e}(a_i)$ maximizes U_{a_i}, we have that

$$X_H + a_H \cdot Y_H \geq X_L + a_H \cdot Y_L \tag{22}$$
$$X_L + a_L \cdot Y_L \geq X_H + a_L \cdot Y_H \tag{23}$$

Adding equations (22) and (23), we find that

$$\begin{aligned} a_H \cdot Y_H + a_L \cdot Y_L \geq a_H \cdot Y_L + a_L \cdot Y_H &\iff (a_H - a_L)Y_H \geq (a_H - a_L)Y_L \\ &\iff Y_H \geq Y_L \end{aligned}$$

since $a_H - a_L > 0$. If $a_H > a_L \geq 0$, then by adding a_L times equation (22) and a_H times equation (23), we find that

$$\begin{aligned} a_L \cdot X_H + a_H \cdot X_L \geq a_L \cdot X_L + a_H \cdot X_H &\iff (a_H - a_L) \cdot X_L \geq (a_H - a_L) \cdot X_H \\ &\iff X_L \geq X_H \end{aligned}$$

which completes the proof. □

Proof of proposition 6:

Proof. The person at every moment maximizes her perceived utility, which is given by

$$B(\tilde{\boldsymbol{e}}) - \sum_{t=1}^{T} \tilde{D}(\tilde{e}_t) = B(\tilde{\boldsymbol{e}}) - (1-\alpha) \sum_{t=1}^{T} D(\tilde{e}_t) - \alpha D'(s) \sum_{t=1}^{T} \tilde{e}_t$$

Since $\sum_{t=1}^{T} \tilde{e}_t = E$ by assumption – the person needs to complete a given amount of work – at every moment she maximizes $B(\tilde{\boldsymbol{e}}) - (1-\alpha) \sum_{t=1}^{T} D(\tilde{e}_t)$ and the claim follows. □

Proof of proposition 7.

Proof. The agent solves the following maximization problem:

$$\max_{\boldsymbol{e}} B - \sum_{t=1}^{T} D(e_t), \text{ s.t. } \sum_{t=1}^{T} p_t \cdot e_t = E$$

where B is a fixed benefit for completing E total work, and p_t is the productivity in period t, that is the amount of effective work done for each unit of effort exerted. This means that actual FOCs are

$$\frac{D'(e_t^*)}{p_t} - \frac{D'(e_{t'}^*)}{p_{t'}} = 0 \forall t, t^{'}$$

Let us assume that all chosen effort levels are determined by binding FOCs. The results hold also if we allow for corner solutions, but are more tedious to derive. Suppose that the agent has exerted s effort on the first day, so that current marginal disutility is $D'(s)$. Then they currently perceive the FOCs as:

$$\frac{\tilde{D}'(\tilde{e}_t^*(s))}{p_t} - \frac{\tilde{D}'(\tilde{e}_1^*(s))}{p_1} = 0$$

where $\tilde{e}_t^*(s)$ is the day-t effort the person considers as optimal on day 1 after having completed s amount of work. Thus they keep working as long as $s < \tilde{e}_1^*(s)$.

Let us rewrite the FOC:

$$\begin{aligned}
&\frac{\tilde{D}'(\tilde{e}_t^*(s))}{p_t} - \frac{\tilde{D}'(\tilde{e}_1^*(s))}{p_1} = 0 \\
\iff &(1-\alpha) \cdot \left(\frac{D'(\tilde{e}_t^*(s))}{p_t} - \frac{D'(\tilde{e}_1^*(s))}{p_1} \right) + \alpha \cdot D'(s) \left(\frac{1}{p_t} - \frac{1}{p_1} \right) = 0 \\
\iff &\frac{D'(\tilde{e}_t^*(s))}{p_t} - \frac{D'(\tilde{e}_1^*(s))}{p_1} = -\frac{\alpha}{1-\alpha} \cdot D'(s) \left(\frac{1}{p_t} - \frac{1}{p_1} \right) \\
\iff &\frac{D'(\tilde{e}_t^*(s))}{p_t} - \frac{D'(\tilde{e}_1^*(s))}{p_1} = \lambda(s)
\end{aligned}$$

where $\lambda(s) = \frac{\alpha}{1-\alpha} \cdot D'(s)(\frac{1}{p_t} - \frac{1}{p_1})$ is strictly positive and strictly increasing in s, since $D'(s)$ is strictly increasing in s.

Claim: $\tilde{e}_1^*(\lambda)$ is strictly decreasing in λ, and hence $\tilde{e}_1^*(s)$ strictly decreases the larger $\lambda(s)$ is

Suppose by contradiction that there is $\lambda(s) > \lambda(s')$ with $\tilde{e}_1^*(s) \geq \tilde{e}_1^*(s')$. Then

$$\begin{aligned}
&\frac{D'(\tilde{e}_1^*(s))}{p_1} \geq \frac{D'(\tilde{e}_1^*(s')}{p_1} \\
\implies &\frac{D'(\tilde{e}_1^*(s))}{p_1} + \lambda(s) > \frac{D'(\tilde{e}_1^*(s')}{p_1} + \lambda(s') \\
\implies &\frac{D'(\tilde{e}_t^*(s))}{p_t} > \frac{D'(\tilde{e}_t^*(s')}{p_t} \\
\implies &\tilde{e}_t^*(s) > \tilde{e}_t^*(s')
\end{aligned}$$

implying that the agent expects to work more in *all* periods, hence would produce more total output under s than under s', which cannot be optimal. This proves the claim.

Case 1: Increasing productivity Let us now assume that productivity is strictly increasing, so that $p_1 < p_2 < ... < p_T$. Then $\lambda(s)$ is strictly increasing in $D'(s)$ and hence in s.

We will show the following in turn:

1. The agent works strictly less on the first day than they should
2. At the start of every day after the first, the biased agent has completed strictly less work in total than the unbiased agent
3. On every day that is not the first or the last, the agent ends up working strictly less than they expected to work on this day at the end of the day before

Step 1: We will show that $\tilde{e}_1^* < e_1^*$, where $\tilde{e}_1^*$ is the actual amount of effort the projection-biased agent ends up exerting, and e_1^* is the optimal amount they should be exerting. This amount is determined as before: the agent works as long as their currently perceived optimal work on day 1 is not yet reached. Formally, they work as long as $s < \tilde{e}_1^*(s)$ and stop once $s = \tilde{e}_1^*(s)$ – which must occur as long as $\tilde{e}_1^*$ is continuous in s, since it is strictly decreasing in s. Continuity of $\tilde{e}_1^*$ holds since the utility function is strictly concave. Hence the FOC that determines the optimal level has $s = \tilde{e}_1^* > 0$, so by the claim we just proved, we know that the person exerts less effort at $\lambda(\tilde{e}_1^*)$ than they would at $\lambda = 0$, and $\lambda = 0$ corresponds to the *unbiased* case. Hence they work stricly less than they should.

Step 2: Let $E_t = \sum_{i=1}^t p_i \cdot e_i^*$ be the total work completed at the end of day t by the unbiased agent and $\tilde{E}_t = \sum_{i=1}^t p_i \cdot \tilde{e}_i^*$ be the total work completed at the end of day t by the biased agent.

Then we want to show that $\tilde{E}_t < E_t$ for all t from 1 to $T-1$ – since of course at the end of the last day, the person has completed the same amount of work. We know from step 1 that $\tilde{E}_1 = \tilde{e}_1^* < e_1^* = E_1$, so the result holds for $t = 1$. We will prove it by induction. Suppose that the result holds for all $\tau < t$. If $t = T$, then we are done. If $t < T$, then we will prove that the result also holds for $\tau = t$ and hence for all $\tau \leq t$. Thus by induction it holds for all $\tau < T$, proving our claim.

Why does the result hold for $\tau = t$? Suppose by contradiction that it does not hold. Then $\tilde{E}_{t-1} < E_{t-1}$ and $\tilde{E}_t \geq E_t$, hence $\tilde{e}_t^* > e_t^*$. Consider how much the biased agent would work if suddenly on day t they would become unbiased: that is, they can not change the fact that they worked suboptimally in the past, but moving forward they will work optimally. Let us denote this person's variables with a hat rather than a tilde, i.e. $\hat{e}_t^*$ is the amount of effort they will exert on day t. Since day t is the first day of the rest of their life, by step 1 we know that they would work more now than they did as a biased agent: $\hat{e}_t^* > \tilde{e}_t^* \geq e_t^*$. But this means that they started day t having to complete strictly more work on the remaining days than an agent who worked optimally from the start, yet on day $t+1$ they have strictly less work remaining than such an agent, despite both choosing optimally and having convex disutility of effort. This is a contradiction.

Hence step 2 holds.

Step 3: Consider day t such that $t + 1 < T$. Then we want to show that the amount of effort the person expects to exert on day $t+1$ at the end of day t, $\tilde{e}_{t+1|t}^*$, is larger than the amount they will actually exert, $\tilde{e}_{t+1}^*$. WLOG, we can assume that $t = 1$ and $T \geq 3$, since we can always ignore what happened on the first $t-1$ days and treat the remaining problem as a new problem. Thus we want to show that $\tilde{e}_{2|1}^* > \tilde{e}_2^*$. Let us write all FOCs that remain on day 2:

$$\frac{D'(\tilde{e}^*_{t|2})}{p_t} - \frac{D'(\tilde{e}^*_2)}{p_2} = \lambda(\tilde{e}^*_2)$$

At the end of day 1, they are perceived as follows:

$$\frac{D'(\tilde{e}^*_{t|1})}{p_t} - \frac{D'(\tilde{e}^*_{2|1})}{p_2} = \lambda(\tilde{e}^*_1)$$

Since productivity is higher on day 2 than on day 1, we know that $\tilde{e}^*_{2|1} > \tilde{e}^*_1$ – the agent is planning to work more on day 2 than they have worked on day 1. as long as $s \leq \tilde{e}^*_1$.

Thus suppose by contradiction that we have $\tilde{e}^*_2 \leq \tilde{e}^*_1$. Then defining $\lambda_2 := \lambda(\tilde{e}^*_2)$ and $\lambda_1 = \lambda(\tilde{e}^*_1)$, we have $\lambda_2 \leq \lambda_1$. Since day 2 is the first day of the problem starting on day 2, we can apply our claim with λ_2 and λ_1, with λ_2 corresponding to the actual FOCs and λ_1 to the perceived ones at the end of the previous day, and we find that for these λs $\tilde{e}^*_2 = \tilde{e}^*_2(\lambda_2) \geq \tilde{e}^*_2(\lambda_1) = \tilde{e}^*_{2|1} > \tilde{e}^*_1$ – but the final inequality is a contradiction, which proves step 3.

Case 2 Let us now assume that the productivity strictly *decreases* over time. The main difference is that $\lambda(s)$ is now decreasing in $D'(s)$ and in s. Specifically, this implies that the more the person works, the more they are planning to work on day 1. While this might lead to corner solutions where the projection-biased agent does all the work on the first day, I exclude this in the remaining analysis.

We will show the following in turn:

1. The agent works strictly more on the first day than they should
2. At the start of every day after the first, the biased agent has completed strictly more work in total than the unbiased agent
3. On every day that is not the first or the last, the agent ends up working strictly less than they expected to work on this day at the end of the day before

Step 1 Showing that the agent works strictly more is entirely symmetrical to the argument in step 1 for increasing productivity, except that due to $\lambda(s)$ decreasing in s, we get that the biased agent does more work at $\lambda(\tilde{e}^*_1) < 0$.

Step 2 This is essentially identical to the argument in the previous step 2.

Step 3 This argument is again very similar to the previous step 3, but the direction of the result is the same as for increasing productivity. Let us therefore repeat the argument broadly here to highlight why the agent still overestimates how much they will work.

Suppose by contradiction that the person works $\tilde{e}^*_2$, and that this is larger than what they planned, $\tilde{e}^*_{2|1}$. We know that the planned effort on day 2 is lower than actual effort on day 1, since productivity on day 1 is higher: $\tilde{e}^*_1 > \tilde{e}^*_{2|1}$. Since we assume they work at least as much as planned, let us consider what happens once they have exerted effort $\tilde{e}^*_{2|1}$. The λ they perceive at this point for their FOCs is λ_2, which is higher than λ_1 for the FOCs perceived at the end of day 1 – which is exactly the same direction, rather than the reverse direction, from the previous step 3. The reason is that, while $\lambda(s)$ is now decreasing with s rather than increasing, we also have that planned effort on day 2 is lower than actual effort on day 1, the opposite order from the previous step 3. Reversing both of these leads to the same ranking of the FOCs, and hence to the same outcome: higher λ_2 at the planned level means that they are planning to work less than they do for λ_1. In other words, planned effort at $\tilde{e}^*_{2|1}$ is lower than planned effort at $\tilde{e}^*_1$, but the latter is equal to $\tilde{e}^*_{2|1}$, thus the former must be lower than this, which implies that they must have stopped working before reaching this level. $\square$

A.4 Proofs for Section 6

Proof for proposition 8.

Proof. The claims for values of E with $E > E_L$ hold as in the proof of proposition 3, using the fact that there is an S such that $D'(S) > D'(0)$. Thus we need to only check the statements affecting $E < E_L$, that is:

- $\forall E < E_L$, $\exists B$ s.t $\tilde{E} = 0$ and $U(E) > 0$.
- $\forall E < E_H$ if $\tilde{E} > 0$ then $\tilde{E} = E$.

Let's start by identifying E_L and E_H.

Claim 1: If $\bar{E} > 0$, then there is a unique $E_0 > 0$ such that $D'(E_0) = D'(0)$ and $D'(E) < D'(0)$ for $E \in (0, E_0)$ and $D'(E) > D'(0)$ for $E > E_0$.

Proof of claim 1: $D''(E) < 0\ \forall E \in [0, \bar{E})$, and $D''(\bar{E}) = 0$. Thus $D'(E) - D'(0) = \int_0^E D''(e)de < 0$ for all $E \in [0, \bar{E}]$. By assumption, $D'(E) \to \bar{D} > D'(0)$. Therefore, by the intermediate value theorem, there exists some $E_0 \in (\bar{E}, \infty)$ such that $D'(E_0) = D'(0)$. Similarly, $D''(E) > 0$ for $E > \bar{E}$, therefore $D'(E)$ is strictly increasing on $E > \bar{E}$, so there cannot be two such E_0. Since $D'(\bar{E}) < D'(0)$ and since $D'(E)$ is increasing for $E > \bar{E}$, the claim follows.

Claim 2: If $\bar{E} > 0$, there is a unique strictly positive number E_L such that $D(E_L)/E_L = D'(0)$. (Note that if $\bar{E} = 0$, then $D(E)/E > D'(0)$ for all $E > 0$, and thus there is no such E.)

By claim 1, we know that there is a unique $E_0 > 0$ such that $D'(E_0) = D'(0)$, and $D'(E) > D'(0)$ when $E > E_0$ and $D'(E) < D'(0)$ when $0 < E < E_0$. Therefore $D(E)/E < D'(0)$ for $E < E_0$. Moreover, since $D'(E_0 + \varepsilon) > D'(E_0) = D'(0)$, we have that $D(E_0)/E_0$ must eventually become arbitrarily close to $D'(E_0 + \varepsilon)$ and thus exceed $D'(0)$. By the intermediate value theorem there must therefore be a point at which $D(E)/E$ equals $D'(0)$. Denote the first time this happens by E_L.[24] Note that $E_L > E_0$. Then it is easy to see that there is only one such E_L. Suppose there was a second, $E_L^{'} > E_L > E_0$. Then

[24] We should take the infimum over all such points, however given the setup, the infimum is a minimum, hence this makes sense.

$$
\begin{aligned}
D'(0) = \frac{D(E_L^{'})}{E_L^{'}} &= \frac{1}{E_L^{'}} \int_0^{E_L^{'}} D'(e)de \\
&= \frac{1}{E_L^{'}} \left(\int_0^{E_L} D'(e)de + \int_{E_L}^{E_L^{'}} D'(e)de \right) \\
&= \frac{1}{E_L^{'}} \left(D'(0) \cdot E_L + \int_{E_L}^{E_L^{'}} D'(e)de \right) \\
&> \frac{1}{E_L^{'}} \left(D'(0) \cdot E_L + D'(0)(E_L^{'} - E_L)de \right) \\
&= D'(0)
\end{aligned}
$$

which is a contradiction. The inequality comes from the fact that $D'(e) > D'(0)$ for $e > E_0$, which holds when $e > E_L$ since $E_L > E_0$. Note that the proof also shows that $D(E)/E < D'(0)$ when $E < E_L$ and $D(E)/E > D'(0)$ when $E > E_H$.

Let us now prove the main claims we are interested in, namely that $\forall E < E_L$, then

- $\exists B$ s.t $\tilde{E} = 0$ and $U(E) > 0$.
- if $\tilde{E} > 0$ then $\tilde{E} = E$.

Specifically, fixing such an E, we will show that there is a $\bar{B} > D(E)$ s.t. the task is started if and only if $B > B_L$; and that if the task is started it is finished. Given the definition of this $\bar{B}$, we have that $U(E) > 0$ whenever the task is started, and $U(E) > 0$ for some $B < \bar{B}$.

People start a task iff the initial perceived disutility of the task is lower than the benefits:

$$
B \geq \tilde{D}_0(E) = (1-\alpha)D(E) + \alpha D'(0) \cdot E = D(E) + \alpha E \cdot (D'(0) - D(E)/E) = \bar{B}
$$

Since $D'(0) > D(E)/E$ when $E < E_L$, this means that the task needs to be strictly worth it for projection-biased people to start it, and if $B \in (D(E), \bar{B})$, then people don't start the task.

It remains to be shown that if people start a task with $E < E_L$, then they finish it. Since we have shown that such tasks necessarily are worthwhile, since $B \geq \bar{B} > D(E)$ for them to be started, I will show that people finish *all* worthwhile tasks that they start. People stop a task if the remaining perceived disutility at any point, $\tilde{D}_s(E) - \tilde{D}_s(s)$, is larger than the benefits.

$$
B \leq \tilde{D}_s(E) - \tilde{D}_s(s) = (1-\alpha)(D(E) - D(s)) + \alpha D'(s)(E - s)
$$

For tasks that are worthwhile, $D(E) \leq B$, thus $D(E) - D(s) \leq B$. If $D'(s) \leq D'(0)$ then $(1-\alpha)(D(E) - D(s)) + \alpha D'(s)(E-s) < (1-\alpha)D(E) + \alpha D'(0)E \leq B$, since the task was started at time 0. This means that people do not stop before reaching $\bar{E}$, as $D'(s) < D'(0)$ for $s \in (0, \bar{E}]$.

For $s > \bar{E}$, we have that D' is strictly increasing, which implies that $D'(s)(E-s) < \int_s^E D'(e)de = D(E) - D(s) < D(E)$, and therefore $(1-\alpha)(D(E)-D(s)) + \alpha D'(s)(E-s) < (1-\alpha)D(E) + \alpha D(E) = D(E) < B$, so people do not stop. $\square$