

# Time-dependent effect of hydrocortisone administration on intertemporal choice\*

Sandra Cornelisse<sup>†</sup>, Vanessa van Ast<sup>‡</sup>, Johannes Haushofer<sup>§</sup>,  
Maayke Seinstra<sup>¶</sup>, Marian Joëls<sup>†</sup>

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## Abstract

Intertemporal choices, involving decisions which trade off outcomes at different points in time, are often made under stress. Stress activates the hypothalamic-pituitary-adrenal (HPA) axis, resulting in the release of corticosteroids. Recent studies provide evidence that corticosteroids can induce rapid non-genomic effects followed by slower genomic effects that are thought to modulate cognitive function in opposite and complementary ways. It remains unknown, however, how corticosteroids affect intertemporal choice. To target time-dependent effects of cortisol on intertemporal choice, we randomly assigned healthy men to one of three possible groups: 1) receiving 10 mg hydrocortisone 195 minutes (slow cort) or 2) 15 minutes (rapid cort), or 3) placebo at both times, before measuring intertemporal choice by offering subjects decisions between small rewards available sooner vs. large rewards available later, in a double-blind design. We demonstrate a time-dependent effect of cortisol administration on intertemporal choice: when tested 15 minutes after hydrocortisone administration, subjects showed a strongly increased preference for the small, soon reward over the larger, delayed reward. In contrast, this effect was not found when testing occurred 195 minutes after hydrocortisone administration. Together, these results suggest that the physiological effects of acute, but not delayed, stress may increase temporal discounting.

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<sup>†</sup>Department of Neuroscience and Pharmacology, Rudolf Magnus Institute of Neuroscience, University Medical Center Utrecht, 3508 AB, Utrecht, The Netherlands

<sup>‡</sup>Department of Clinical Psychology, University of Amsterdam, Amsterdam, The Netherlands

<sup>§</sup>Abdul Latif Jameel Poverty Action Lab, MIT E53-379, 30 Wadsworth St., Cambridge, MA 02142, USA

<sup>¶</sup>Comparative Psychology, Institute of Experimental Psychology, Heinrich-Heine University, Düsseldorf, 40225, Düsseldorf, Germany

# 1 Introduction

Many everyday decisions entail trading off immediate and delayed outcomes. In such intertemporal choices, both humans and animals tend to value delayed outcomes less than immediate ones, a phenomenon known as temporal discounting (Laibson 1997; Strotz 1956). As a consequence of discounting, people frequently find it difficult to act in accordance with their own long-term goals (Laibson 1997).

In this paper, we ask whether stress hormones affect intertemporal choice. The motivation for posing this question is twofold. First, decades of psychological and neurobiological research on stress have shown that it has broad behavioral effects; in particular, acute stress impairs cognitive flexibility (e.g. reversal learning) and complex problem-solving (e.g. anagrams, Alexander et al. 2007; working memory, Arnsten et al. 1999, Birnbaum et al. 1999; and long-term memory, Domes et al. 2004, Newcomer et al. 1994, (1999), Buchanan et al. 2006, Kuhlmann et al. 2005). However, the effects of stress on economic choice are only beginning to be understood: initial studies have shown that acute stress increases pro-social behavior in economic exchange games (von Dawans et al. 2012), and that it increases risk aversion in the gains domain and risk-seeking in the loss domain (Porcelli and Delgado 2009). But to our knowledge, no study has investigated the effects of stress on intertemporal choice.

Second, previous research supports the plausibility of the hypothesis that stress may affect intertemporal choice. Takahashi (2004) suggested that baseline cortisol levels may be correlated with intertemporal choice. More relevantly, Lerner et al. (2013) show that experimentally induced sadness led to increased discount rates; thus, to the extent that stress induces negative affect, one might expect similar results. On the neural level, brain regions thought to subserve intertemporal choice are targets of stress hormones. Intertemporal choice is thought to be subserved by a network involving brain regions implicated in reward processing such as ventral striatum (McClure et al. 2004), as well as those associated with executive control such as the dorsolateral prefrontal cortex (Figner et al. 2010). Prefrontal cortex, in turn, has a high density of glucocorticoid receptors, which bind cortisol (KIM and HALLER 2007). It therefore appears plausible that stress hormones may affect intertemporal choice.

To test this hypothesis, we combine behavioral economics measures of intertemporal choice with pharmacological manipulation of the stress hormone cortisol. Specifically, we time-dependently administered hydrocortisone to healthy human subjects and then asked them to complete a temporal discounting task. We find strong increases in impatience 15 minutes after hydrocortisone administration, but not 195 minutes later.

The remainder of the paper is organized as follows. Section 2 provides background and

motivation; Section 3 outlines the methods and experimental design; Section 4 presents results; Section 5 concludes.

## 2 Background

Cortisol is a steroid hormone synthesized by the hypothalamic-pituitary adrenal (HPA) axis: in response to external stressors, the hypothalamus secretes corticotrophin-releasing hormone (CRH), which in turn controls the release of adrenocorticotrophic hormone (ACTH) from the pituitary gland; ACTH then causes the release of cortisol from the adrenal gland. Two factors give cortisol its prominent role in stress: first, it is released in response to both psychological and physiological strain on the organism. In the physical domain, it increases following bodily injuries, physical exertion, illness, and extreme temperatures. In the psychological domain, cortisol increases in response to social stressors such as having to give a speech in front of a panel of judges or performing mental arithmetic ([Kirschbaum et al. 1993](#); [Ferracuti et al. 1994](#)). Second, cortisol exerts rapid non-genomic effects as well as slow, genomic effects on the organism that together are thought to allow it to optimally respond to the stressful situation.

Recent evidence suggests that cortisol acts differentially on the organism over short and long time horizons through the rapid and slow mechanisms respectively. In particular, shortly after stress, corticosteroid actions interact with the neurotransmitter noradrenaline to synergistically promote rapid increases in neuronal activity ([Karst et al. 2010](#); [2005](#)). These rapid corticosteroid effects have been described for emotion- and arousal-related brain areas, such as the amygdala ([van Marle et al. 2010](#); [Hermans et al. 2011](#)). They promote emotional and reflex-like behaviour ([Schwabe et al. 2010](#); [Henckens et al. 2012](#)) and attention ([Vedhara et al. 2000](#)), at the expense of goal-directed behaviour ([Schwabe et al. 2010](#)) and higher cognitive functioning ([Elzinga and Roelofs 2005](#)). This may help the organism to focus on the most salient, habitual aspects of an event ([Roozendaal et al. 2006](#)), at the cost of the more complex, cognitive aspects.

By contrast, delayed effects of cortisol on the brain are thought to restore homeostasis following episodes of stress ([Diamond et al. 2007](#); [Joëls et al. 2006](#)). Through changes in gene transcription that require about one hour to develop and last for several hours ([Datson et al. 2008](#)), stress-induced corticosteroid actions shut down the effects of noradrenaline ([Pu et al. 2007](#); [2009](#); [Joëls and de Kloet 1989](#)) and change neuronal activity in frontal brain regions such that the stress-induced release of hormones from the pituitary is terminated ([Hill et al. 2011](#); [Yuen et al. 2009](#)). Behaviorally, these slower genomic effects promote consolidation ([Barsegyan et al. 2010](#)), contextual memory ([Oitzl et al. 2001](#)), enhance working memory

(Henckens et al. 2011), promote sustained attentional processing (Henckens et al. 2012), and strengthen connectivity between the PFC and amygdala (Henckens et al. 2010). Thus, slower genomic corticosteroid effects may facilitate processing and remembering a stress episode in a cognitively controlled manner and allow the organism to learn from it for the future.

We hypothesized that this bi-directional effect of cortisol on behavior is also apparent in more complex behavioral responses, such as intertemporal choice. Because the early physiological responses to cortisol are thought to shift the focus to the present, we expected stronger discounting immediately after hydrocortisone administration. By contrast, because the restorative functions of the slower actions of cortisol are thought to prepare the organism for the future, we expected to find an increased focus on the future several hours after hydrocortisone administration.

## 3 Materials and Methods

### Participants

The sample was restricted to male participants to minimize confounds from hormonal fluctuations during the female cycle. A total of 79 male subjects gave written informed consent. Sample size was determined by a power analysis (power  $> 0.80$ ;  $\alpha = 0.05$ ) for detecting medium (Cohen’s  $d$  ranging from 0.50 to 0.80) interaction effects. The local ethical committee of the University of Amsterdam approved the study. Inclusion criteria as assessed by self-report were: no past or present psychiatric or neurological condition, and age between 18 and 35 years. Men having any somatic or endocrine disease (e.g., acute asthma), or taking any medication known to influence central nervous system or endocrine systems were excluded from participation. Further, subjects were asked to refrain from taking any drugs three days prior to participation, and to get a night of proper sleep, refrain from heavy exercise, alcohol and caffeine intake 12 hours prior to participation, and not to eat, drink, smoke, or brush teeth two hours before participation. Subjects were rewarded for their participation with a show-up fee of € 30 (this fee could alternatively be exchanged for course credit); in addition, a single trial of the intertemporal choice task was randomly chosen for payment (maximum € 20).

### Drug administration and assessment

Hydrocortisone and placebo (albochin) treatments were administered through identically appearing pills. A single dose of 10 mg of hydrocortisone was employed to elevate endogenous cortisol to a level equivalent to moderate acute stress (Abercrombie et al. 2003). To assess

salivary free cortisol concentrations in each subject throughout the experiment, participants were asked at different times to lightly chew on Salivette collection devices (Sarstedt, Nümbrecht, Germany) for one minute, or until it was completely saturated with saliva. Cortisol levels were assessed at 9 time points spread throughout the experiment (Figure 1). After testing, the salivettes were stored at  $-25^{\circ}\text{C}$ . Upon completion of the entire study, samples were analyzed for salivary free cortisol concentrations using a commercially available chemiluminescence immunoassay (CLIA) with high sensitivity of 0.16 ng/ml (IBL, Hamburg, Germany) by Technische Universität, Dresden, Germany.

## Intertemporal choice task

Participants performed 6 blocks of an intertemporal choice task with varying delays, where decisions between a sooner smaller reward and a later larger reward were offered. In the first four blocks subjects had the choice between a smaller reward tomorrow, and a larger reward in a) 3 months and 1 day, b) 6 months and 1 day, c) 9 months and 1 day, and d) 12 months and 1 day. In the last two blocks, subjects chose between a smaller reward in 6 months and 1 day, and a larger reward in e) 9 months and 1 day, and f) 12 months and 1 day. The short delay was purposefully set to ‘tomorrow’ rather than today to keep implied transaction costs the same for sooner and later payments (see below for details on transaction costs). Each block consisted of 7 binary choice trials, resulting in a total of 42 trials. The larger reward was kept constant at an amount of € 20, while the sooner smaller reward started at € 10 and was then adjusted with a titration method according to the choices the subject made.

Titration is a standard method for identifying time preferences in the discounting literature (Mazur 1988; Green and Myerson 2004; Kable and Glimcher 2007). The titration worked as follows: for each choice of the later reward, the sooner reward was increased by half the difference between it and € 20; for instance, if a subject chose € 20 in 12 months and 1 day over € 10 tomorrow, the next trial would offer the subject a choice between € 20 in 12 months and 1 day and € 15 tomorrow; if the subject still chose € 20 in 12 months and 1 day, the next offer would be € 20 in 12 months and 1 day vs. € 17.50 tomorrow, and so on. For each choice of the sooner reward, the sooner reward was decreased by half of the difference between it and the previously offered soon reward. For instance, if a subject chose € 10 tomorrow over € 20 in 12 months and 1 day, the next trial would offer the subject a choice between € 5 tomorrow and € 20 in 12 months and 1 day; if the subject chose € 5 tomorrow, the next offer would be € 2.50 tomorrow vs. € 20 in 12 months and 1 day, and so on. The titration procedure lasted for 7 trials at each combination of delays; this means that each indifference point was identified to a precision of € 0.0781 ( $\text{€ } 10 \times 0.57$ , i.e.

the initial difference between € 10 and € 20/ € 0 was halved seven times). The amount of the sooner reward at the end of this titration procedure was taken as the indifference point for the particular delay combination, i.e. the amount of the sooner smaller reward where participants switched between the smaller sooner and the later larger reward.

In our analysis, we consider two measures of time preference. First, we use the proportion of choices of the delayed option as an outcome variable. Second, we computed the area under the curve described by all the indifference points. This is a parameter-free measure of time preference and does not require functional form assumptions about the discount function. For both measures, large values correspond to less discounting. Note that both dependent variables described above collapse subjects' choices in the time preference task into a single parameter; thus, each subject enters each the statistical analysis only once, i.e. we are not using multiple (non-independent) data points for each subject. Possible serial correlation and order effects in subjects' responses were controlled for by randomizing the order of trials across blocks, i.e. the order in which the various indifference points were determined. In addition, the side of the screen (left or right) on which the “late” and “soon” options were presented on each trial was randomized across trials.

Reimbursement consisted of the show-up fee of € 30, plus the amount chosen by the subject in a randomly chosen trial of the intertemporal choice task. Due to a restriction imposed by the human subjects committee, all subjects were paid the entire amount on the day of the experiment. We took two approaches to preserve the integrity of the intertemporal choice task while avoiding deception. First, subjects were informed before the experiment that they would receive a show-up fee of € 30 and the amount they chose in one of the trials of the intertemporal choice task; no information was given about the timing of the payment. This approach is similar to that taken by other experiments in economics (Karlan and Zinman 2010), in which “surprising” subjects with better conditions than they originally chose (the terms of a microfinance loan in the case of Karlan & Zinman) is thought to elicit accurate responses from participants while remaining ethically acceptable. Second, at the end of the experiment, each subject reported whether or not they believed that they would receive the chosen amount at the corresponding delay. In total, there were 27 subjects that indicated that they did not believe this (7 in the rapid cort group, 11 in the slow cort group and 9 in the placebo group). We include a robustness check in our analysis in which we exclude “payment non-believers”.

## Design and General Procedure

In a between-subjects, placebo-controlled, double blind study design, participants were randomly assigned to either the rapid cort (hydrocortisone 15 min prior to testing) or slow cort (hydrocortisone 195 min prior to testing) or placebo group (see experimental outline in Figure 1). Testing took place in between 12 pm and 8 pm, when endogenous cortisol levels are stable and relatively low (Pruessner et al. 1997).

Upon arrival, participants read an information brochure, were screened by means of an interview to assess eligibility for participation, signed the informed consent and filled out the Barratt Inhibition Scale (BIS; Patton and Stanford 1995) to control for potential individual differences in choice tendencies. Baseline self-reported mood state was assessed with the Positive Affect and Negative Affect Schedule (PANAS; Watson et al. 1988), and a first baseline saliva sample was collected.

Directly following a second baseline sample, participants received their first pill (cortisol or placebo). To ascertain that cortisol levels would return to baseline in the slow cort group, a three-hour waiting period followed, during which participants either read or studied in the same room as the remainder of the experiment. During this time, subjects were provided lunch, and four more saliva samples were obtained at regular intervals (see Figure 2).

The second pill (cortisol or placebo) was given three hours after the first. A second resting period of 15 min followed, with the purpose to allow cortisol plasma levels to reach their peak following administration (Czock et al. 2005) and activate non-genomic effects in the brain for the rapid cort condition. Participants then gave another saliva sample and again filled out the mood questionnaires (PANAS), followed by the intertemporal choice task. A final saliva sample was taken and the post-experimental questionnaire assessed 1) whether participants believed that their monetary decisions would indeed be rewarded in the promised amount at the promised time, 2) whether subjects knew which substance they had received at what time.

## Econometric approach

Statistical analysis was performed using the Stata and SPSS statistical software packages (StataCorp, College, Station, TX; SPSS Inc., Chicago, Illinois). Group differences in sample characteristics were assessed by univariate ANOVAs with the between subject factor Group (rapid cort, slow cort, placebo). The effect of hydrocortisone administration on intertemporal choice was assessed by estimating the following model:

$$y_i = \beta_0 + \beta_1 T_i^{\text{SHORT}} + \beta_2 T_i^{\text{LONG}} + \varepsilon_i \quad (1)$$

Here, the outcome variable  $y_i$  is either the proportion of choices of delayed rewards for subject  $i$ , or the area under the curve described by their indifference points.  $T_i^{\text{SHORT}}$  and  $T_i^{\text{LONG}}$  are treatment dummies denoting the rapid vs. slow cort conditions; and  $\varepsilon_i$  is the usual idiosyncratic error term. Standard errors are not clustered because each subject enters the analysis only once, and subjects participated in the study individually. As a robustness check, we also estimate the following modified version of the model:

$$y_i = \beta_0 + \beta_1 T_i^{\text{SHORT}} + \beta_2 T_i^{\text{LONG}} + \beta_3 \mathbf{X}_i + \varepsilon_i \quad (2)$$

Here,  $\mathbf{X}_i$  is a vector of control variables, which include age and body-mass index (BMI).

Finally, to assess whether the results differed between subjects who believed that they were going to receive payment for the intertemporal choice task after the delay associated with the trial that was chosen for payment from those subjects who did not believe this, we estimate the same two models on a restricted sample in which only subjects who believed the payment information are included.

## 4 Results

### Manipulation Check

The rapid cort, slow cort and placebo groups did not differ in terms of age, body mass index and score on the BIS scale (all  $F$ s < 0.48, n.s.). Figure 2 displays the salivary cortisol levels for the three experimental groups during the experiment. As expected, the ANOVA for salivary cortisol levels showed a significant time  $\times$  condition interaction ( $F_{14,518} = 139.68$ ;  $p < 0.001$ ,  $\eta^2 = 0.791$ ). In addition, a significant main effect of Time ( $F_{7,518} = 47.16$ ,  $p < 0.001$ ,  $\eta^2 = 0.389$ ) and Condition ( $F_{2,74} = 55.01$ ,  $p < 0.001$ ,  $\eta^2 = 0.598$ ) emerged. Bonferroni-corrected post-hoc comparisons showed that in the slow cort condition cortisol levels were increased from 30 min after pill intake until 180 min later ( $S3 - S6$ ;  $ps < 0.002$ ) and in the rapid cort condition cortisol levels were increased from 30 min after pill intake until the end of the session ( $S7 - S8$ ;  $p$ 's < 0.001). The exit interview showed that participants were unable to identify the substance received ( $X^2(1) = 0.298$ , n.s.). Furthermore, the experimental manipulation (cortisol/placebo administration) did not differentially affect subjective mood (PANAS) between the groups (all  $F$ 's < 2.77, n.s.).



## Intertemporal choice performance

Figure 3 displays the intertemporal choice performance (mean indifference points) of the three experimental groups. Table 1 reports the group means and standard errors for the three experimental groups and the two outcome variables. The proportions of “delayed” choices in the intertemporal choice task show that subjects in the placebo condition chose the large, delayed payment over the small, soon payment 77% of the time, while those in the slow cort condition chose it 71% of the time, and those in the rapid cort condition 68% of the time.

When subjects who did not believe the payment information were excluded from the sample, the results were similar, with 76% of subjects choosing the delayed payment under placebo, 75% under slow cort, and 66% under rapid cort. Similarly, the area under the curve was on average  $181.88 \pm 10.05$  ( $183.77 \pm 11.74$  when “payment non-believers” were excluded) for subjects in the placebo condition,  $167.68 \pm 11.25$  ( $182.16 \pm 14.83$ ) in the slow cort condition, and  $152.45 \pm 9.69$  ( $145.47 \pm 11.62$ ) in the rapid cort condition. Thus, both dependent measures suggest that the rapid cort group discounts more steeply than the other two groups, and there is some indication that the slow cort group also discounts more than placebo.

Table 2 reports the results of ordinary least squares regressions of the proportion of delayed choices and area under the curve on dummies for the two treatment groups. The coefficients on the rapid cort treatment dummy are negative and highly significant in all specifications, showing that hydrocortisone administration leads to increased discounting 15 minutes after administration relative to placebo. This was true for both dependent measures, i.e. the proportion of choices of the delayed payment, and the area under the curve described by the indifference points; in addition, the results were robust to the inclusion of age and BMI as control variables, with the coefficients remaining highly similar after inclusion of these variables. Exclusion of the subjects who did not believe that they would receive payment as suggested by the intertemporal choice task did not alter the coefficients noticeably.

There were no significant differences in our measures of discounting between the slow cort condition and the placebo condition. Comparing the rapid and slow cort conditions, we found marginally significant effects ( $p < 0.10$ ) when payment non-believers were excluded from analysis, suggesting that the rapid cort condition increased discounting to a moderately greater extent than the slow cort condition. This was true for both dependent variables and both with and without the inclusion of control variables. Thus, subjects in the rapid cort condition exhibited fewer choices of the larger, delayed payment, and a smaller area under the curve described by the indifference points than the placebo condition. The negative effect of hydrocortisone administration on the propensity to choose large delayed over small,

soon rewards was only observed when behavioral testing occurred 15 min. after cortisol administration, but not (and in, some cases, significantly less so) when it occurred 195 min. after administration.

A potential challenge to the interpretation of our results in terms of reflecting an effect of cortisol on time preference is that subjects in the rapid cort condition may simply have made more errors in their choices, leading to an apparently greater rate of discounting (Franco-Watkins et al. 2006). To rule out this possibility, we asked whether treatment assignment affected the consistency of subjects' time preferences. We defined inconsistency as the proportion of pairs of adjacent indifference points which exhibited a negative rate time preference, despite an average positive rate of time preference for that subject. Put differently, a pair of adjacent indifference points is classified as inconsistent if the indifference point for the longer delay is higher than that for the shorter delay. We then regressed this measure on treatment assignment, as shown in Table 3. Two results are worth noting. First, the proportion of inconsistent pairs of adjacent indifference points was small, at 5.6% on average. Second, hydrocortisone administration had no effect on inconsistency; all associated coefficients are insignificant. Thus, it is unlikely that our results simply reflect an increase in noise in subjects' choice behavior.

## 5 Discussion

We here demonstrate an effect of hydrocortisone administration on intertemporal choice. More specifically, cortisol increases impatience and lowers the area under the curve described by individual indifference points immediately after hydrocortisone administration, but does not affect these parameters when subjects are tested several hours later.

This rapid effect of cortisol on impatience is in line with current views that shortly after stress, individuals turn to simple behavioral strategies. For instance, humans exposed to a psychosocial stressor use a simpler (striatal) stimulus-response rather than a more complex spatial learning strategy (Schwabe et al. 2007). Individuals also shift from goal-directed to habitual control in instrumental behavior shortly after stress (Schwabe et al. 2010). This is accompanied by the activation of a salience network (Hermans et al. 2011). Underlying biological mechanisms of these rapid stress effects are thought to involve both catecholamines and corticosteroid hormones (Schwabe et al. 2007; 2010a; 2010b; Joëls et al. 2011), the latter probably accomplishing non-genomic actions (Karst et al., 2005). Our results show directly that pharmacologically induced increases in cortisol levels lead to greater impatience. Whether the rapid behavioral effects involving the prefrontal-striatal circuitry are due to non-genomic corticosteroid cellular actions – similar to those described e.g. for hippocampal

neurons (Karst et al. 2005) – is presently unknown.

We did not find any significant effects of corticosteroid administration on temporal choice performance when tested several hours after administration. Subjects in the delayed cortisol condition performed similarly to subjects in the placebo condition, suggesting that intertemporal choice behavior normalizes in the aftermath of stress. Thus, we find evidence that intertemporal choice performance was restored to baseline performance several hours after cortisol administration, but no evidence for our prediction of opposite effects, i.e. less discounting in the slow cortisol condition.

Our results complement and extend several previous studies of the effect of stress hormones and negative affect on decision-making. Most relatedly, Lerner et al. (2013) demonstrate that experimentally induced negative affect increases discount rates. Our own work has recently shown that social stressors, such as the Trier Social Stress Test, may not affect intertemporal choice (Haushofer et al. 2013). One possible explanation for the divergent findings of the present study and our previous work is that social stressors may not produce a sufficient increase in cortisol levels to generate a behavioral effect on intertemporal choice. More broadly, however, a number of studies have shown that stress hormones affect choice behavior. It should also be emphasized that the current pharmacological approach is optimal to delineate the effect of hydrocortisone by itself but does not recapitulate the situation of stress where multiple hormones (in addition to cortisol) are being released.

The work of Schwabe and colleagues has shown that the joint actions of cortisol and norepinephrine favor habitual at the expense of goal-directed behavior (Schwabe et al. 2010). This increase in habitual responding is broadly consistent with our finding of increased impatient responding under the influence of hydrocortisone in light of the fact that impatient responding in intertemporal choice tasks is commonly understood to be partly due to impulsive responses. However, we obtain this effect in the absence of concurrent noradrenergic stimulation, suggesting that some behaviors may be affected by cortisol alone. Similarly, Keinan (1987) found that subjects were impaired in a verbal analogy task when they were threatened with uncontrollable compared to controllable electric shocks. Gray (1999) found that subjects made suboptimal decisions in a temporally extended choice task when the task was presented in a negative emotional compared to a neutral context. Van den Bos et al. (2009) and Preston et al. (2007) found that performance on the Iowa Gambling Task was impaired under stress, particularly in men. Finally, Porcelli & Delgado (2009) induced stress using the cold-pressor task, in which subjects immerse their hand in ice-cold water, and found that this stress induction increased the reflection effect in risky decision-making: stressed subjects showed stronger risk aversion in the gains domain, and stronger risk seeking in the loss domain.

Our study extends these previous findings on risky choice into the intertemporal domain; to our knowledge, our experiment is the first to test the effect of hydrocortisone administration on intertemporal choice, and its dependency on the timing of choice relative to hydrocortisone administration. One limitation of our study is that the soonest delay available was tomorrow, which precludes studying decreasing impatience; future studies will need to explore different time scales, varying both the delay between hydrocortisone administration and the task, as well as the rewards delays within the intertemporal choice task, to fully understand the complexity of the effects of stress and stress hormones on intertemporal choice. Moreover, the intertemporal choice task in the present study was not fully incentivized, in the sense that subjects were paid the amount of a randomly chosen trial from the intertemporal choice task, but this payment was made on the same day as the experiment, raising the possibility that the behavioral effect may have been underestimated.

Together, our findings suggest that time preference is not a stable trait, as traditionally assumed in economic theory (Samuelson 1937; Lancaster 1963), but is strongly susceptible to environmental and somatic factors, such as individuals' responses to stress and variations in hormonal balance. Regardless of the internal mechanisms, the fragility of time preference and its complex dependence on stress need to be considered in the design of optimal policies aiming at decisions that are consistent with an individual's long-term economic interests.

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Table 1: Summary statistics

		Choose delay		Area under the Curve	
		(1)	(2)	(3)	(4)
Cort, rapid	Mean	0.68	0.66	152.45	145.47
	SE	0.02	0.03	9.69	11.62
	N	26	19	26	19
Cort, slow	Mean	0.71	0.75	167.68	182.16
	SE	0.03	0.04	11.25	14.83
	N	26	15	26	15
Placebo	Mean	0.77	0.76	181.88	183.77
	SE	0.02	0.03	10.05	11.74
	N	27	18	27	18
Sample		All	Payment believers	All	Payment believers

*Notes:* Summary statistics for the effect of rapid and slow hydrocortisone conditions or placebo on intertemporal choice. Columns 1 and 2 report the proportion of "delayed" choices in the intertemporal choice task; columns 3 and 4 reports the area under the curve formed by the individual difference points. Each cell shows the mean, standard error of the mean, and number of observations. Standard errors are not clustered because each subject enters the analysis only once and subjects participated in the study individually.

Table 2: Effects of hydrocortisone administration on intertemporal choice

	Choose delay				Area under the Curve			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cort, rapid	-0.0887*** (0.0333)	-0.0904*** (0.0338)	-0.0976** (0.0397)	-0.0990** (0.0409)	-29.43** (13.96)	-29.26** (14.24)	-38.30** (16.55)	-37.11** (17.40)
Cort, slow	-0.0594 (0.0392)	-0.0632 (0.0390)	-0.0116 (0.0485)	-0.0132 (0.0500)	-14.21 (15.08)	-14.56 (15.31)	-1.62 (18.87)	-1.14 (19.40)
Age		0.00606 (0.00441)		0.00697 (0.00515)		1.76 (1.74)		2.37 (1.97)
BMI		-0.00799 (0.00652)		-0.00625 (0.00800)		-1.24 (2.30)		-0.29 (2.93)
Constant	0.765*** (0.024)	0.817*** (0.170)	0.759*** (0.028)	0.749*** (0.188)	181.9*** (10.1)	171.6*** (62.8)	183.8*** (11.8)	136.8*** (73.7)
Sample	All	All	Payment believers	Payment believers	All	All	Payment believers	Payment believers
Rapid vs.slow F (p)	0.59 (0.45)	0.50 (0.48)	3.16* (0.08)	3.07* (0.09)	1.05 (0.31)	0.96 (0.33)	3.81* (0.06)	3.49* (0.07)
Joint significance F (p)	3.61** (0.03)	3.68** (0.03)	3.39** (0.04)	3.32** (0.04)	2.23 (0.11)	2.11 (0.13)	3.23** (0.05)	2.80* (0.07)

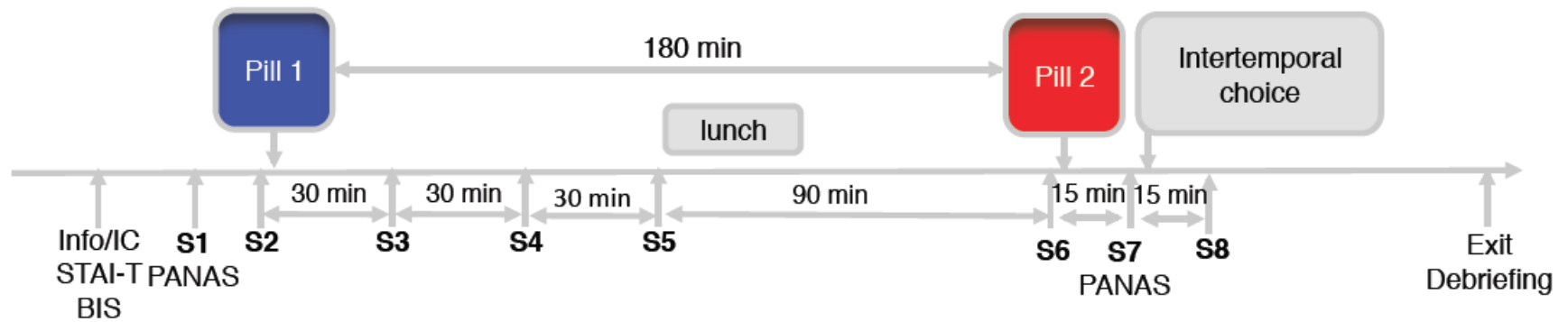
*Notes:* Ordinary least squares regression for the effects of the rapid and slow hydrocortisone conditions on behavior in the intertemporal choice task. Columns (1)-(4) report the effect of hydrocortisone on the proportion of "delayed" choices in the intertemporal choice task; columns (5)-(8) on the Area under the Curve formed by the individual difference points. Robust standard errors are shown in parentheses. Standard errors are not clustered because each subject enters the analysis only once and subjects participated in the study individually. The last two rows show F-tests comparing the rapid and slow cort conditions. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Table 3: Effects of hydrocortisone administration on inconsistent responding in intertemporal choice

	Inconsistent
Cort, rapid	0.0502 (0.0376)
Cort, slow	0.0310 (0.0395)
Constant	0.0556*** (0.0204)
Observations	79

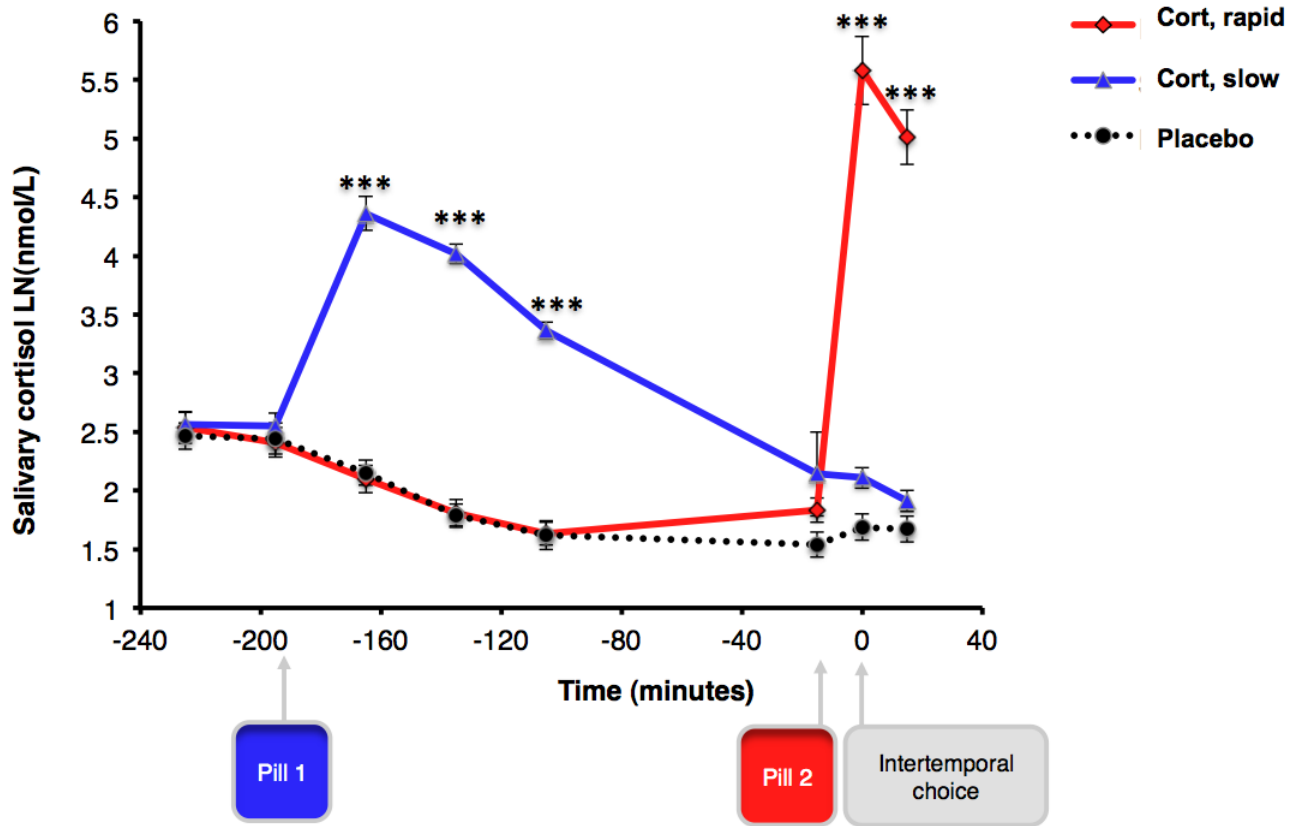
*Notes:* Ordinary least squares regression for the effect of rapid and slow cort conditions on inconsistent responses in time preference task. Inconsistency is defined as the proportion of adjacent indifference points for which subjects discount the future negatively, despite discounting positively on average. Robust standard errors in parentheses. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Figure 1: Timeline of the experiment



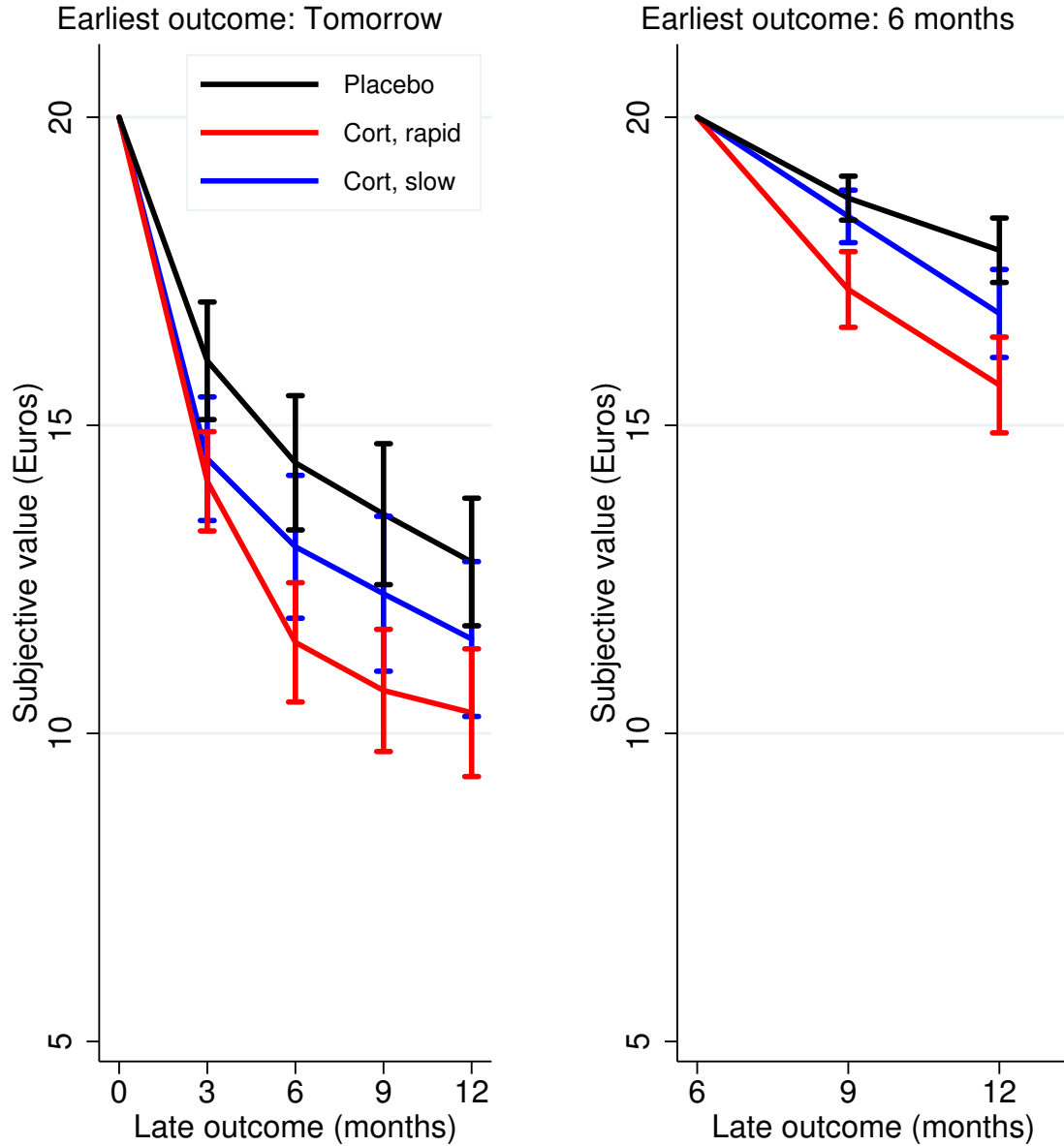
*Notes:* Timeline of the experiment. Upon arrival, participants read the information brochure (Info), filled out the informed consent (IC) and the behavioral inhibition scale (BIS). As a manipulation check of the cortisol manipulation, saliva samples were taken throughout the experiment (S1-S8). Time in between the samples was fixed and is indicated with gray arrows. The first and second pills (Pill 1 and Pill 2) were administered directly after S1 and S6, respectively. Positive and negative affect (PANAS) was measured at the same time as S1 and S7. The intertemporal choice task took place immediately after S7

Figure 2: Salivary cortisol curves for the three experimental groups



*Notes:* Participants received a pill 195 minutes (pill 1) and 15 minutes (pill 2) prior to the intertemporal choice task ( $t = 0$ ) could contain 10 mg hydrocortisone or placebo (albochin). Hydrocortisone administration in both groups significantly elevated salivary cortisol as compared to placebo, but did not differ immediately before each pill intake. Throughout the experiment, saliva samples were taken at 225, 195, 165, 135, 105, 15 and 0 minutes before intertemporal choice, and 15 minutes after. Error bars represent standard error of the mean (SEM). Significant Bonferroni-corrected differences with placebo are depicted by  $*** = p < 0.005$ .

Figure 3: Intertemporal choice performance



*Notes:* Intertemporal choice performance of placebo (black), short delay (red), and long delay (blue) groups. Shown are mean indifference points  $\pm 1$  SEM. The subjective value of an indifference point can be interpreted as the amount at which a subject is indifferent between receiving that amount tomorrow vs. receiving 20 Euros after a specified delay. Lower indifference points therefore indicate greater discounting. The left panel shows discounting between tomorrow and 3, 6, 9, and 12 months from tomorrow; the right panel shows discounting between 6 months and 9 and 12 months.