Outcome value and task aversiveness impact task procrastination through separate neural pathways

Zhang, S.M.; Verguts, T.; Zhang, C.Y.; Feng, P.; Chen, Q.; Feng , T.Y.

Cerebral Cortex, August 2021;31: 3846–3855

https://doi.org/10.1093/cercor/bhab053
Advance Access Publication Date: 12 April 2021
Original Article

ORIGINAL ARTICLE

Outcome Value and Task Aversiveness Impact Task Procrastination through Separate Neural Pathways

Shunmin Zhang[1,2], Tom Verguts[3], Chenyan Zhang[4], Pan Feng[1], Qi Chen[5,7] and Tingyong Feng[1,6]

[1]School of Psychology, Southwest University, Chongqing 400715, China, [2]Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou 310000, China, [3]Department of Experimental Psychology, Ghent University, Ghent B-9000, Belgium, [4]Institute of Psychology, Leiden University, Leiden 9500 2300, Netherlands, [5]School of Psychology, Center for Studies of Psychological Application and Guangdong Key Laboratory of Mental Health and Cognitive Science, South China Normal University, Guangzhou 510631, China, [6]Key Laboratory of Cognition and Personality, Ministry of Education, Chongqing 400715, China and [7]Key Laboratory of Brain, Cognition and Education Sciences, Ministry of Education, Guangzhou, China

Address correspondence to Tingyong Feng, School of Psychology, Southwest University, No. 2 Tian Sheng Road, Beibei, Chongqing 400715, China. E-mail: fengty0@swu.edu.cn; or Qi Chen, School of Psychology, South China Normal University, No. 55, West of Zhong Shan Avenue, Guangzhou 510631 China. Email: chen.qi@m.scnu.edu.cn.

Abstract

The temporal decision model of procrastination has proposed that outcome value and task aversiveness are two separate aspects accounting for procrastination. If true, the human brain is likely to implicate separate neural pathways to mediate the effect of outcome value and task aversiveness on procrastination. Outcome value is plausibly constructed via a hippocampus-based pathway because of the hippocampus's unique role in episodic prospection. In contrast, task aversiveness might be represented through an amygdala-involved pathway. In the current study, participants underwent fMRI scanning when viewing both tasks and future outcomes, without any experimental instruction imposed. The results revealed that outcome value increased activations in the caudate, and suppressed procrastination through a hippocampus-caudate pathway. In contrast, task aversiveness increased activations in the anterior insula, and increased procrastination via an amygdala–insula pathway. In sum, this study demonstrates that people can incorporate both outcome value and task aversiveness into task valuation to decide whether to procrastinate or not; and it elucidates the separate neural pathways via which this occurs.

Key words: amygdale–insula coupling, dual-process theory, hippocampus-striatum coupling, procrastination, task valuation

Procrastination is a stable harmful tendency within individuals, a heritable trait across generations (Gustavson et al. 2014), and a widespread problematic behavior across different cultures (Steel and Ferrari 2013). This behavior consistently harms people's work efficiency, health, and psychological well-being (Sirois, 2007, 2015; Stead et al. 2010). A recent temporal decision model suggests that procrastination results from devalued future outcomes and overwhelming task aversiveness (Zhang and Feng 2020). Specifically, people are less likely to procrastinate a task when finding its future outcome more valuable (Prévost et al. 2010), but more likely to procrastinate when finding the task aversive (Onwuegbuzie and Collins 2001). This model regards future outcomes and task aversiveness as two dissociable task aspects producing procrastination. If this view is correct, the human brain is likely to implicate separate neural pathways to mediate their effects on procrastination.

The temporal decision model suggests that future outcomes and task aversiveness play dissociable roles in leading to

procrastination. Theoretically, driven by valuable future outcomes along, people would complete a task as soon as possible. On the contrary, in the face of task aversiveness only, people would be reluctant to do this task forever. In realistic situations, a task generally contains both valuable future outcomes and task aversiveness. Thus, people choose not to do a task now but to do it later (i.e., procrastination). As the temporal decision model revealed, people choose to procrastinate because of expecting higher outcome value but perceiving less task aversiveness to do a task later than immediately (Zhang and Feng 2020). Accordingly, people indeed expect the future self to be more motivated by outcomes than the present self (Steel et al. 2018). On the other hand, the present self also perceives less aversiveness to do a task later than immediately (Sirois and Pychyl 2013). Together, future outcomes and task aversiveness act as two separate forces that jointly make people procrastinate.

Despite a correlation in phenomenology (Krause and Freund 2016), distinct neural pathways might represent outcome value and task aversiveness. The representation of future outcomes likely relies on episodic prospection (Boyer 2008), whereas task aversiveness is an emotional response (Bechara and Damasio 2005; Clore and Huntsinger 2007). Among episodic prospection brain regions, hippocampus is the only one consistently reported by studies replicating interaction between prospection and decisions (Sasse et al. 2015; Hu et al. 2017). On the other hand, various studies have revealed that amygdala mediates emotional contributions to decision making, including brain lesion studies (Gupta et al. 2011), neurons recording studies (Jenison et al. 2011), and neuroimaging studies (Seymour and Dolan 2008). Accordingly, Yonelinas and Ritchey (2015) suggested that a hippocampus-centered cognitive system is specialized for episodic representation, whereas an amygdala-based affective system is specialized for quick emotional processing. Hence, outcome value and task aversiveness might be evaluated through a hippocampus-based and an amygdala-based pathway, respectively.

Many studies suggest that the hippocampus can provide episodic information to shape reward-related activity in the ventral striatum, guiding goal-directed behavior (Pennartz et al. 2011). Theoretically, both future rewards and future punishments could motivate task engagement (Strunk et al. 2013). Nevertheless, the present study focuses on the neural representation of rewarding outcomes because few tasks are motivated by future punishments in the current data set. Striatum codes the subjective value of a wide range of rewards (Balleine et al. 2007; Izuma et al. 2008), including future outcomes (Zhang et al. 2019). The representation of outcome value thus might involve a hippocampus-striatum circuit. In line with this proposal, a hippocampus-striatum coupling indeed increased when episodic memory guides decisions by impacting evaluating options (Wimmer and Shohamy 2012). On the other hand, amygdala might constitute the emotional pathway with anterior insula which responds to the aversion to various stimuli (Sarinopoulos et al. 2010; Heeren et al. 2016). Indeed, altered amygdala–insula connections predict emotional disorders like anxiety disorder and posttraumatic stress disorder (Rabinak et al. 2011; Roy et al. 2013; Bebko et al. 2015; Nicholson et al. 2016). Amygdala–insula coupling also processed emotional stimuli like fearful faces (Fonzo et al. 2010; Gorka et al. 2015). Therefore, we hypothesized that outcome value and task aversiveness impact procrastination through a hippocampal-striatal pathway and an amygdala–insula pathway, respectively.

To test these hypotheses, we measured participants' neural signals while freely viewing personal tasks and corresponding future outcomes. Briefly, we collected personal tasks and future outcomes, and measured ratings of outcome value, task aversiveness, and task procrastination individually in a prescan interview. Two days after the prescan interview, we separately presented personalized tasks and future outcomes indicated by verbal cues to encourage participants to construct them spontaneously in a functional magnetic resonance imaging (fMRI) scanner. Using the ratings obtained in the prescan interview, we searched neural pathways separately mediating the effects of outcome value and task aversiveness on task procrastination. Of note, this study also validated and features a free viewing method, in which participants can spontaneously generate thoughts related to future outcomes and task aversiveness (see Supplementary Experiment and Fig. S1). Thus, this method guarantees high ecological validity and allows us to investigate the neural mechanism in an uncontaminated manner.

Materials and Methods

Participants

A total of 41 right-handed volunteers were recruited to test our hypotheses; none of these participants reported a history of psychiatric or neurological disorder. Data collection was approved by the Institutional Review Board of a local university. All participants provided written informed consent. Due to excessive head movement (>2 mm or >2°) during the fMRI acquisition, data from five participants were excluded, leading to 36 participants (nine males, mean age = 21.1 years, $SD = 1.65$) in the final analysis. The sample size was chosen to ensure adequate power to detect an assumed medium-size effect (effect size $\rho = 0.5$, type I error $\alpha = 0.05$, power $1\text{-}\beta = 0.90$) based on a G*Power calculation, which resulted in a minimum sample size of 34 participants.

Prescan Interview

We collected real-life tasks and outcomes and measured ratings on outcome value, task aversiveness, and task procrastination 2 days before scanning. We choose 2 days as the interval for two considerations. First, a 2-day interval could serve as a buffer to diminish the potential priming effects of a prescan interview on fMRI scanning. Second, the measures obtained in the prescan interview would still be representative because the tasks would not change dramatically after 2 days (Zhang and Feng 2020). In this prescan interview, participants were asked to list self-planned tasks (number of tasks: $M = 6.46$, $SD = 0.77$) and future outcomes for those tasks. All participants offered only one primary future outcome for each task, and explicitly indicated whether this future outcome was rewarding or punishing. They also rated frequency of procrastination on a 1–5 scale ("Do you procrastinate on this task?": 1 = not at all; 2 = almost no; 3 = occasionally; 4 = often; 5 = always). In the current study, only tasks with future rewarding outcomes are modeled in fMRI analysis because the number of tasks motivated by future punishing outcomes was too small. For example, half of the participants offered none or only one task motivated by punishing future outcomes. We also collected task aversiveness and outcome value to investigate neural pathways mediating their effects on procrastination. Specifically, outcome value refers to how desirable a rewarding outcome is when the task is completed (or how aversive a punishing outcome is when the task is failed).

Participants rated outcome value for each task separately on 0–8 scales (ranging from "not at all" to "extremely"). Participants rated task aversiveness on the question "how aversive are you going to feel if you have to start or complete [a certain task] within 24 h" on a 0–8 scale (0 indicates "totally neutral", 8 indicates "extremely unpleasant") for each task. We choose "within 24 h" instead of "immediately" since participants arrived at the lab at a different time of the day. Besides, we collected the deadline before which the task had to be done for each task to control its effect on procrastination (Ariely and Wertenbroch 2002).

fMRI Experiment

In an fMRI scanner, each participant viewed personalized tasks and outcomes obtained in the prescan interview. Data were collected via a mixed block/event-related design (see Fig. 1), incorporating separate blocks for tasks and future outcomes. The present study used a total of five separate runs, each lasting 6 min 6 s. A task block alternated with a future outcome block within each run until the run ended. We balanced block order (i.e., task block first or future outcome block first) across runs and participants. Each specific task (in task blocks) or future outcome (in future outcome blocks) was presented precisely once in each block. Within each block, a cue indicating a task (e.g., essay writing) or future outcome (e.g., a good grade) was separately presented for a duration of 10 s in a randomized order without repetition. The tasks and outcomes were not repeated only within each block but were repeated between blocks. A fixation cross was presented during the intertrial intervals (ITIs) for 4 s (2–6) s on average. To promote free viewing of the personalized tasks and associated future outcomes, participants were instructed to "Just think of whatever comes to mind related to the cued words" without further constraints. After the fMRI scanning, participants reported how many thoughts relevant to the cued word were evoked for each task and future outcome (from 0, indicates none, to 8, indicates extremely abundant). According to these post measures, both the thoughts related to tasks and future outcomes are abundant (for thoughts related to tasks, $M = 4.37$, $SD = 1.67$; for thoughts related to outcomes, $M = 4.58$, $SD = 1.85$).

fMRI Data Acquisition and Preprocessing

The data were acquired on a Siemens 3 T MRI system (Siemens Magnetom Trio TIM, Erlangen, Germany) using a T2*-weighted echoplanar BOLD-sensitive sequence with interleaved acquisition [64×64; 3×3 mm pixels; repetition time (TR), 2000 ms; echo time (TE), 30 ms; flip angle 90°]. Each volume comprised 32 axial slices (3 mm slice thickness) allowing whole brain coverage. A total of 183 volumes were acquired for each of the five runs. Before preprocessing, the first three volumes were discarded to allow for T1 equilibration effects. Additionally, MPRAGE (magnetization-prepared rapid-acquisition gradient echo) structural images were acquired (250×250; 1 mm^3 cubic voxels; 176 slices; TR, 1900 ms; TE, 2.52 ms; flip angle 9°).

fMRI data were analyzed using SPM12 (http://www.fil.ion.ucl.ac.uk/spm/software/spm12/). Preprocessing included correction for differences in slice acquisition time, realignment, and coregistration with the structural image. Next, the structural images were spatially normalized to the Montreal Neurological Institute (MNI) space and the resulting normalization parameters were applied to the functional images using fourth-degree B-spline interpolation and a resolution of $3 \times 3 \times 3$ mm^3. The images were finally smoothed using an isotropic 8 mm full-width half-maximal Gaussian kernel.

ROI Selection

This study adopted small volume correction with predefined spherical ROIs (radium = 10 mm) based on previous studies. We selected a striatal ROI (MNI coordinates: $x = -8$, $y = 10$, $z = 14$) coding outcome value and an insular (MNI coordinates: $x = -24$, $y = 22$, $z = 10$) ROI coding task cost from (Treadway et al. 2012) because their paradigm meets the following three conditions. Their paradigm is sensitive to individual differences in both negative affect and motivation for future rewards (Treadway et al. 2009). Second, their paradigm can predict real-life individual differences in exerting effort to pursue long-run outcomes (a weight-loss treatment) (Mata et al. 2017). Third, their work revealed potentially separate brain regions for coding task aversiveness and outcome value, respectively (Treadway et al. 2012). We also selected a meta-analysis hippocampal ROI (MNI coordinates: $x = -26$, $y = -38$, $z = -10$) responsible for episodic prospection (Stawarczyk and D'Argembeau 2015), and a meta-analysis amygdala ROI (MNI coordinates: $x = -22$, $y = -6$, $z = -12$) responsible for emotional memory processing (Murty et al. 2010). The hippocampal ROI will assist the search of the hypothesized hippocampus-striatum pathway, while the amygdala ROI will help the search of the amygdala–insula pathway of interest.

The current study performed small volume correction on both cluster level and peak (voxel) level in SPM12. The cluster-level correction controls the family-wise error (FWE) rate by defining minimum contiguous voxel size under an initial height threshold at some uncorrected P-value. This study chooses $P = 0.005$ as the initial height threshold as many researchers and software tools have recommended this P-value. The peak-level correction controls the FWE rate of an ROI by imposing a height threshold. Any voxels with a T-value higher than the height threshold can be considered significant on the peak level.

Behavioral Data Analysis

We intend to test whether the model with both task aversiveness and outcome value best predict task procrastination than alternative models. To this aim, this study implemented mixed linear models and compared those models using the likelihood ratio test via the lme4 package. The mixed linear model is well suited to investigate relationships between variables (fixed effects) by controlling higher-level group factors (random effects). Specifically, we compared two models with either task aversiveness or outcome value as a predictor with another model with both of them as predictors. In those models, outcome value and task aversiveness were involved as the fixed factors, while participants and outcome type (rewards or punishments) were involved as the random factor to control for their intraclass differences (i.e., random intercept models).

Neuroimaging Data Analysis

We have two aims in neuroimaging data analysis. First, we searched for striatal activations that respond to outcome value and insular activations that respond to task aversiveness. Second, we tested whether there are hippocampus-striatal

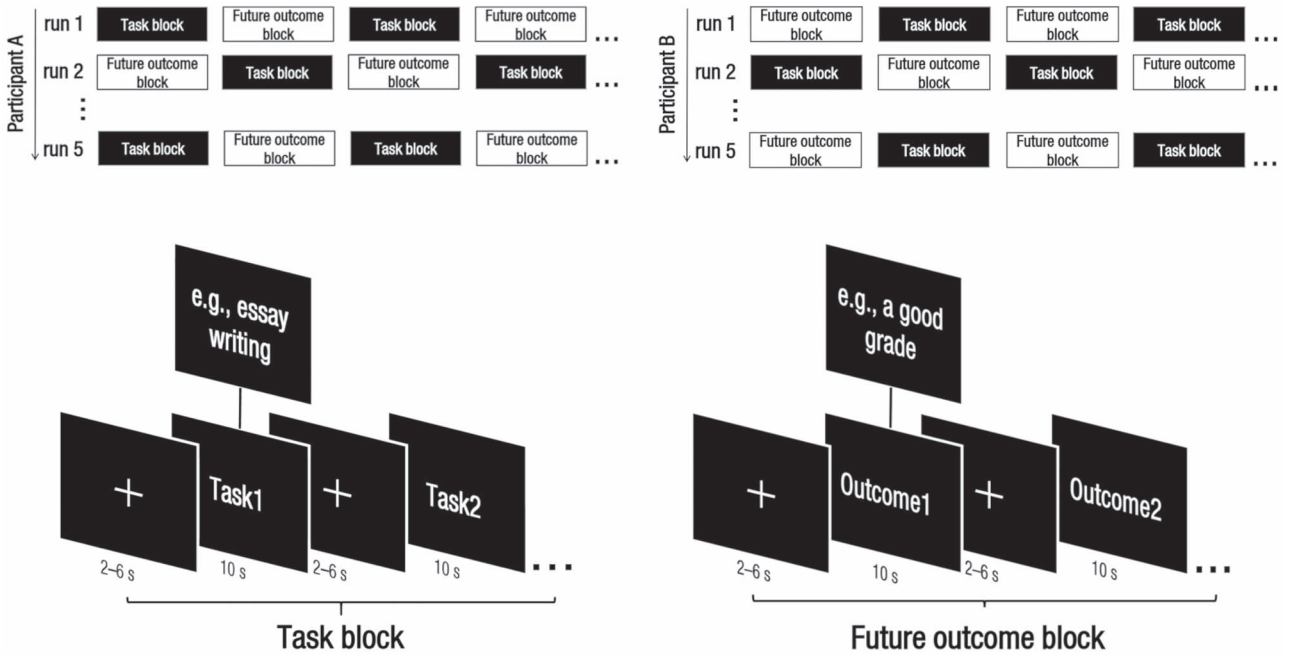

Figure 1. Experimental design enabling free viewing of personalized tasks and outcomes during fMRI scanning. Free viewing encourages thinking whatever related to cues. Verbal cues of tasks and outcomes were separately presented in a task block and a future outcome block. The order of a task block and a future outcome block was balanced across runs and participants. Within each run, a task block and a future outcome block were presented in alternating order. In each block, tasks or future outcomes were presented one at a time in a random order without repetition. The abundance of thoughts related to cues was measured right after scanning.

couplings and amygdala–insula couplings that support our hypotheses.

To search for striatal (or insular) activation, we first generated neural-contrast signals related to the presentation of future outcomes (or aversive tasks) at a within-subject level. Then, we looked for neural-contrast signals that are positively associated with outcome value (or task aversiveness) in the striatal (or insular) ROI at a between-subject level. Specifically, we performed a mean-split on each participant's tasks and outcomes according to personal mean procrastination frequency, yielding high- and low-procrastination groups. The first-level neural-contrast signals were generated by comparing neural signals that respond to future outcomes (or aversive tasks) between high- and low-procrastination groups within each participant. Then, we regressed those contrasts responding to future outcomes (or aversive tasks) across participants with corresponding outcome value (or task aversiveness) difference.

To search for the hypothesized hippocampus-striatum (or amygdala–insula) couplings, we first generated couplings with striatum (or insula) using PPI analysis (Friston et al. 1997) at a within-subject level. Then, we tested whether there are hippocampus-striatum (or amygdala–insula) couplings that support our hypothesis at a between-subject level. Specifically, the PPI analysis revealed differences in functional coupling with striatum (or insula) for each participant when viewing future outcomes (or aversive tasks) between high- and low-procrastination groups. Then, we regressed those hippocampus-striatum (or amygdala–insula) couplings with corresponding outcome value (or task aversiveness) difference across participants. Next, we looked for hippocampus-striatum (or amygdala–insula) couplings that are positively associated with outcome value (or task aversiveness) within our hippocampal (or amygdala) ROI. Finally, we examined our hypothesis by testing the mediating role of the identified hippocampus-striatum (or amygdala–insula) couplings between outcome value (or task aversiveness) and procrastination.

Results

More Procrastinated Tasks Are Associated with Lower Outcome Value but Higher Task Aversiveness

Using ratings collected in the prescan interview, we found that increasing task procrastination was associated with decreasing outcome value ($t = -3.64$, $P < 0.001$, $CI = [-0.20, -0.06]$, $N = 232$) and increasing task aversiveness ($t = 8.47$, $P < 0.001$, $CI = [0.21, 0.33]$, $N = 232$) (see Fig. S2). This result also survived when the deadline was included as a covariate (for outcome value: $t = -3.50$, $P < 0.001$, $CI = [-0.17, -0.05]$, $N = 232$; for task aversiveness: $t = 6.11$, $P < 0.001$, $CI = [0.13, 0.26]$, $N = 232$). Model comparisons also revealed that the model that involves both outcome value and task aversiveness outperformed the models that involve only outcome value or task aversiveness (see Table 1), indicating that people evaluate both outcome value and task aversiveness to form the subjective value of a task.

We included both rewarding outcomes and punishing outcomes in the behavioral analysis because they did not impact procrastination differently ($t = 0.50$, $P > 0.25$, $CI = [-0.13, 0.21]$, $N = 232$). Of note, the tasks motivated by punishing outcomes were not included in fMRI analysis because few participants reported enough tasks motivated by punishing outcomes.

Table 1 Model comparisons against the model which predicts procrastination with both outcome value and task aversiveness

Model	ΔAIC	ΔBIC	R^2	$\chi^2_{(1)}$	Sig.
Outcome value + Task aversiveness	0	0	0.41	-	-
Outcome value	53.67	50.54	0.09	−55.67	<0.001
Task aversiveness	10.32	7.19	0.34	−12.32	<0.001

Note: The ΔAIC (ΔBIC) is the difference in AIC (BIC) obtained by subtracting those of the model involves both outcome value and task aversiveness. Smaller AIC or BIC indicates better performance of a model. The $\chi^2_{(1)}$ and statistical significance (Sig.) were obtained from model comparisons against the model which involves both outcome value and task aversiveness by the likelihood ratio test. AIC: Akaike information criterion, BIC: Bayesian information criterion.

Outcome Value Suppresses Procrastination through a Hippocampus-Caudate Pathway

To focus on activations in the striatum, we adopted small volume correction with the predefined striatal ROI (see ROI selection). As we expected, a caudate cluster of striatum showed increasing neural signals with the increase of outcome value difference across participants (cluster level $P_{FWE\text{-}SVC} < 0.05$, peak level $P_{FWE\text{-}SVC} < 0.05$, see Fig. 2a). This result supports our hypothesis that striatum codes outcome value.

Next, we generated functional couplings with caudate using PPI analysis (Friston et al. 1997) with the caudate as a seed (centered at x = 6, y = 9, z = 21; with 6 mm as radius). As expected, there were hippocampus-caudate couplings that were positively associated with outcome value difference across participants (cluster level $P_{FWE\text{-}SVC} = 0.05$, peak level $P_{FWE\text{-}SVC} = 0.06$, see Fig. 2b). More interestingly, a mediation analysis (Preacher & Hayes, 2008) at between-subject level revealed the hippocampus-caudate coupling (ROI centered at x = 26, y = −38, z = −10; with 6 mm as radius) significantly mediated the effect of the outcome value on procrastination (bias corrected $CI = [-0.54, -0.09]$, $N = 36$; see Fig. 2c). Of note, this mediating effect still holds up after involving task aversiveness as a covariable (bias-corrected $CI = [-0.55, -0.07]$), ruling out potential confounds of task aversiveness in the mediation analysis. Together, these results indicated that outcome value suppresses procrastination through a hippocampal-caudate pathway.

Task Aversiveness Drives Procrastination through an Amygdala–Insula Pathway

The results showed that insular signals indeed increased with the increase of task aversiveness difference across participants (cluster level $P_{FWE\text{-}SVC} < 0.05$, peak level $P_{FWE\text{-}SVC} < 0.05$, see Fig. 3a), suggesting that task aversiveness is represented in the anterior insula. Furthermore, we found amygdala–insula couplings were positively associated with task aversiveness difference across participants (cluster level $P_{FWE\text{-}SVC} = 0.08$, peak level $P_{FWE\text{-}SVC} < 0.01$, see Fig. 3b). More interestingly, the amygdala–insula coupling (ROI centered at x = −30, y = 0, z = −18; with 6 mm as radius) indeed significantly mediated the effect of task aversiveness on procrastination (bias-corrected $CI = [0.00, 0.47]$, $N = 36$, see Fig. 3c). This mediating effect also remains after controlling potential confounds of outcome value by involving it as a covariable (bias-corrected CI = [0.03, 0.50]).

Of note, we also tested whether the chosen neural pathways play a selective mediating role as hypothesized. The results revealed that the amygdala–insula coupling cannot significantly mediate the effects of outcome value on procrastination as the hippocampus-caudate couplings do (bias-corrected $CI = [-0.27, 0.05]$). Accordingly, the hippocampus-striatum couplings cannot take the place of the mediating role of amygdala–insula coupling between task aversiveness and procrastination neither (bias-corrected $CI = [-0.06, 0.27]$). To sum, our findings revealed two separate neural pathways mediating the opposite effects of outcome value and task aversiveness on procrastination.

Discussion

The present study specified the neural mechanism underlying the representation of outcome value and task aversiveness. Specifically, outcome value was represented in the caudate, and it suppressed procrastination through a hippocampus-caudate pathway. In contrast, task aversiveness was coded in the anterior insula and drove procrastination through an amygdala–insula pathway. Together, these results demonstrate that people evaluate outcome value and task aversiveness through separate neural pathways.

It is noteworthy that the current study adopted a free viewing method to reveal the neural mechanism underlying task valuation. The free viewing method (Frankort et al. 2012) gives no instruction on how tasks or future outcome should be evaluated, thus allows participants to evaluate tasks and future outcomes in their own way (Ferguson and Bargh 2004; Papies et al. 2007). Because the free viewing method allows participants to evaluate tasks as they prefer, it is also unbiased in testing theories on procrastination. Supporting the temporal decision model (Zhang and Feng 2020), the current study indicates that participants spontaneously incorporated outcome value and task aversiveness into task valuation (see Figs S1 and S2).

The current study revealed that outcome value was coded in the caudate, and suppressed procrastination through an increased hippocampus-caudate coupling. In line with the role of the caudate in representing outcome value, it has been reported that caudate is responsible for anticipation of a wide range of rewarding outcomes (Schultz 2000; Preuschoff et al. 2006; Mizuno et al. 2008), and is also implicated in representing outcomes with different valence (Hariri et al. 2006). Of note, human decision-makers showed increased hippocampus-caudate coupling when retrieving relevant memories to simulate and evaluate future outcomes (Johnson et al. 2007; Shadlen and Shohamy 2016). However, rats with a disrupted hippocampal–striatum interaction were strongly biased to make shorted-sighted choices (Abela et al. 2015). Thus, these results suggest that the abnormalities in the parahippocampal cortex in high procrastinators might also be related to deficits in evaluating future outcomes (Zhang et al. 2016; Hu et al. 2018; Liu and Feng 2018). Supporting this possibility, many studies have confirmed that hippocampus facilitates the evaluation of future outcomes through its role in episodic simulation (Peters and Büchel 2010; Benoit et al. 2011; Barron et al. 2013; Lebreton

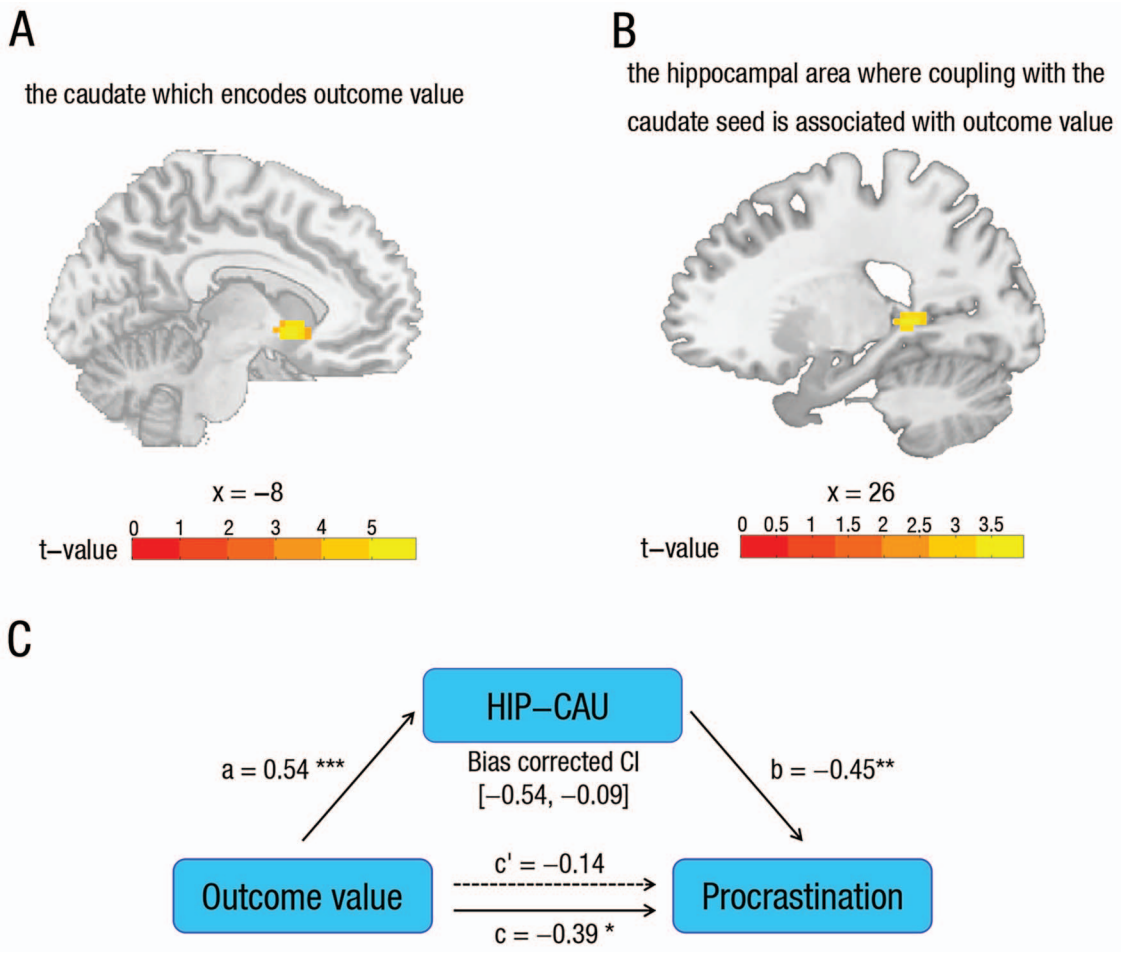

Figure 2. Outcome value was coded in the caudate and impacted procrastination through a hippocampal-caudate pathway. **a** Interindividual differences in caudate signals were positively associated with the corresponding outcome value. **b** The hippocampal area whose coupling with caudate is positively associated with outcome value across participants. **c** The interindividual variabilities in hippocampus-caudate coupling mediated the effect of the corresponding outcome value on procrastination. HIP = hippocampus, CAU = caudate. * indicates $P < 0.05$, ** indicates $P < 0.01$, *** indicates $P < 0.001$.

et al. 2013). On the contrary, the dysfunction of hippocampus reduced the choice of the delayed high reward in favor of the immediately available low reward (McHugh et al. 2008; Abela and Chudasama 2013).

In contrast, the current study suggested that task aversiveness was represented in the anterior insula and exacerbated procrastination through an amygdala–insula pathway. The amygdala–insula coupling is likely to promote procrastination by constructing negative emotions. The anterior insular cortex involves processing different aversive stimuli, such as disgust, aversion, and pain (Ploghaus et al. 1999; Wicker et al. 2003; Huettel et al. 2006). Similarly, it is suggested that amygdala facilitates judgment and decision making by autonomically triggering emotional responses (Bechara and Damasio, 2005; Gupta et al. 2011). The negative emotions triggered by amygdala enable animals to avoid threatening and aversive stimuli (Vazdarjanova et al. 2001; Machado et al. 2009), and help humans avoid disadvantageous options and potential money losses (Bechara and Damasio 2005; Schlund and Cataldo 2010). Of note, the insula and amygdala have anatomical and functional connections (Baur et al. 2013). Furthermore, the amygdala–insula coupling becomes stronger after repeated negative stimuli (Denny et al. 2014).

This result strengthens the temporal decision model's emphasis that outcome value and task aversiveness act independently to impact procrastination (Zhang and Feng 2020). Similarly, dual-process theorists also agree that there is one neural system responsible for rapid, parallel, and automatic processes, whereas another relatively separate system enables uniquely human facilities, such as hypothetical thinking, mental simulation, and consequential decision making (Evans 2003; Frankish 2010). In dual-process theories, task aversiveness might be represented through the former system because emotions are responsible for faster evaluation (Bechara and Damasio 2005; Clore and Huntsinger 2007). In contrast, representation of future outcome is believed to involve mental simulation, thus depends on the latter system (Evans and Stanovich 2013; McClure and Bickel 2014). Thus, it is reasonable for the temporal decision model to take both outcome value and task aversiveness into consideration when linking task value to procrastination.

One thing needs to be stressed. The present study only revealed some possible neural pathways selectively instead of exclusively. For example, episodic prospection involves many brain regions, including hippocampus, media prefrontal cortex (mPFC), para-hippocampus (PHC), medial temporal gyrus (MTG), and posterior cingulate cortex (PCC) (Benoit and Schacter 2015;

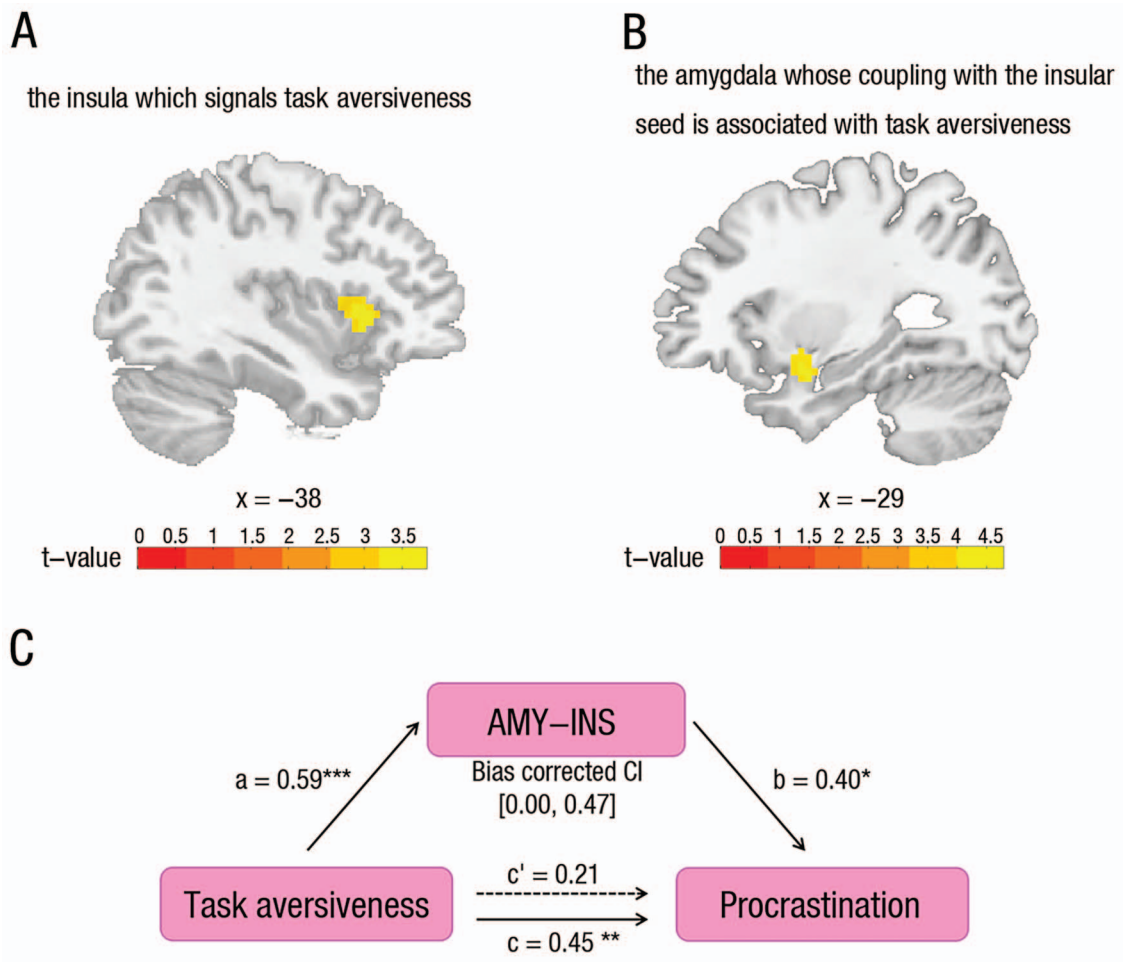

Figure 3. Task aversiveness was represented in the anterior insula and had an effect on procrastination through an amygdala–insula pathway. **a** Interindividual differences in anterior insula signal were positively associated with corresponding task aversiveness. **b** The amygdala whose coupling with the insular seed is associated with task aversiveness across participants. **c** The interindividual variabilities in amygdala–insula coupling mediated the effect of corresponding task aversiveness on procrastination. AMY = amygdala, INS = insula. ** indicates $P < 0.01$, *** indicates $P < 0.001$.

Stawarczyk and D'Argembeau 2015). Thus, some other neural pathways might also participate in mediating the effects of outcome value on procrastination. To test those alternative pathways, we also separately tested the mediating role of striatal couplings with other episodic prospection brain ROIs defined according to the same meta-analysis study (Stawarczyk and D'Argembeau 2015). The result showed that none of those alternative neural pathways significantly mediate the effect of outcome value on procrastination (see Fig. S3). These results imply that the hippocampus might play a unique role in the prospection-decision interaction. In line with this proposal, many researchers believe hippocampus can provide episodic information for evaluation and decision making (Peters and Büchel 2011; Palombo et al. 2015; Shadlen and Shohamy 2016). Empirical studies also confirmed that hippocampal firing rate encodes information of delayed rewards and expected outcomes independent sensory features (Lee et al. 2012; Wikenheiser and Redish 2015; Masuda et al. 2020). Thus, it is worthwhile for future studies to test the unique role of hippocampus in prospection and decision interactions, perhaps with different neural modalities. For example, recent studies revealed that white-matter functional connectomes could provide extra information on cognitive abilities (Sacco et al. 2015; Li et al. 2020a) and mental disorders besides functional coupling in brain gray-matter (Fan et al. 2020; Li et al. 2020b).

In summary, the current study revealed that outcome value was represented in the caudate and can suppress procrastination through a hippocampus-caudate pathway. In contrast, task aversiveness was coded in the anterior insula and can drive procrastination via an amygdala–insula pathway. Together, these results demonstrate that people can incorporate both outcome value and task aversiveness into task valuation through distinct neural pathways. Thus, people should ignore neither outcome value nor task aversiveness when intervening procrastination.

Supplementary Material

Supplementary material can be found at Cerebral *Cortex* online.

Notes

Conflict of Interest: All the co-authors declare that they have no conflict of interest.

Funding

This study was supported by the National Natural Science Foundation of China (31971026, 31800959 and 32071049), and

the Fundamental Research Funds for the Central Universities (SWU2009104,SWU118091).

References

Abela AR, Chudasama Y. 2013. Dissociable contributions of the ventral hippocampus and orbitofrontal cortex to decision-making with a delayed or uncertain outcome. *Eur J Neurosci*. 37:640–647.

Abela AR, Duan Y, Chudasama Y. 2015. Hippocampal interplay with the nucleus accumbens is critical for decisions about time. *Eur J Neurosci*. 42:2224–2233.

Ariely D, Wertenbroch K. 2002. Procrastination, deadlines, and performance: self-control by precommitment. *Psychol Sci*. 13:219–224.

Balleine BW, Delgado MR, Hikosaka O. 2007. The role of the dorsal striatum in reward and decision-making. *J Neurosci*. 27:8161–8165.

Barron HC, Dolan RJ, Behrens TE. 2013. Online evaluation of novel choices by simultaneous representation of multiple memories. *Nat Neurosci*. 16:1492–1498.

Baur V, Hänggi J, Langer N, Jäncke L. 2013. Resting-state functional and structural connectivity within an insula-amygdala route specifically index state and trait anxiety. *Biol Psychiatry*. 73:85–92.

Bebko G, Bertocci M, Chase H, Dwojak A, Bonar L, Almeida J, Perlman SB, Versace A, Schirda C, Travis M. 2015. Decreased amygdala–insula resting state connectivity in behaviorally and emotionally dysregulated youth. *Psychiatry Res Neuroimaging*. 231:77–86.

Bechara A, Damasio AR. 2005. The somatic marker hypothesis: a neural theory of economic decision. *Games Econ Behav*. 52:336–372.

Benoit RG, Gilbert SJ, Burgess PW. 2011. A neural mechanism mediating the impact of episodic prospection on farsighted decisions. *J Neurosci*. 31:6771–6779.

Benoit RG, Schacter DL. 2015. Specifying the core network supporting episodic simulation and episodic memory by activation likelihood estimation. *Neuropsychologia*. 75:450–457.

Boyer P. 2008. Evolutionary economics of mental time travel? *Trends Cogn Sci*. 12:219–224.

Clore GL, Huntsinger JR. 2007. How emotions inform judgment and regulate thought. *Trends Cogn Sci*. 11:393–399.

Denny BT, Fan J, Liu X, Guerreri S, Mayson SJ, Rimsky L, New AS, Siever LJ, Koenigsberg HW. 2014. Insula–amygdala functional connectivity is correlated with habituation to repeated negative images. *Soc Cogn Affect Neurosci*. 9:1660–1667.

Evans JSB. 2003. In two minds: dual-process accounts of reasoning. *Trends Cogn Sci*. 7:454–459.

Evans JSB, Stanovich KE. 2013. Dual-process theories of higher cognition: advancing the debate. *Perspect Psychol Sci*. 8:223–241.

Fan Y, Li L, Peng Y, Li H, Guo J, Li M, Yang S, Yao M, Zhao J, Liu H, et al. 2021. Individual-specific functional connectome biomarkers predict schizophrenia positive symptoms during adolescent brain maturation. *Hum Brain Mapp*. 42:1475–1484.

Ferguson MJ, Bargh JA. 2004. Liking is for doing: the effects of goal pursuit on automatic evaluation. *J Pers Soc Psychol*. 87:557–572.

Fonzo GA, Simmons AN, Thorp SR, Norman SB, Paulus MP, Stein MB. 2010. Exaggerated and disconnected insular-amygdalar blood oxygenation level-dependent response to threat-related emotional faces in women with intimate-partner violence posttraumatic stress disorder. *Biol Psychiatry*. 68:433–441.

Frankish K. 2010. Dual-process and dual-system theories of reasoning. *Philos Compass*. 5:914–926.

Frankort A, Roefs A, Siep N, Roebroeck A, Havermans R, Jansen A. 2012. Reward activity in satiated overweight women is decreased during unbiased viewing but increased when imagining taste: an event-related fMRI study. *Int J Obes*. 36:627–637.

Friston K, Buechel C, Fink G, Morris J, Rolls E, Dolan R. 1997. Psychophysiological and modulatory interactions in neuroimaging. *Neuroimage*. 6:218–229.

Gorka SM, Fitzgerald DA, Labuschagne I, Hosanagar A, Wood AG, Nathan PJ, Phan KL. 2015. Oxytocin modulation of amygdala functional connectivity to fearful faces in generalized social anxiety disorder. *Neuropsychopharmacology*. 40:278–286.

Gupta R, Koscik TR, Bechara A, Tranel D. 2011. The amygdala and decision-making. *Neuropsychologia*. 49:760–766.

Gustavson DE, Miyake A, Hewitt JK, Friedman NP. 2014. Genetic relations among procrastination, impulsivity, and goal-management ability implications for the evolutionary origin of procrastination. *Psychol Sci*. 25:1178–1188.

Hariri AR, Brown SM, Williamson DE, Flory JD, Harriet DW, Manuck SB. 2006. Preference for immediate over delayed rewards is associated with magnitude of ventral striatal activity. *J Neurosci*. 26:13213–13217.

Heeren G, Weber B, Reuter M, Markett S, Montag C. 2016. Loss aversion is associated with bilateral insula volume. A voxel based morphometry study. *Neurosci Lett*. 619:172–176.

Hu X, Kleinschmidt H, Martin JA, Han Y, Thelen M, Meiberth D, Jessen F, Weber B. 2017. A reduction in delay discounting by using episodic future imagination and the association with episodic memory capacity. *Front Hum Neurosci*. 10:663.

Hu Y, Liu P, Guo Y, Feng T. 2018. The neural substrates of procrastination: a voxel-based morphometry study. *Brain Cogn*. 121:11–16.

Huettel SA, Stowe CJ, Gordon EM, Warner BT, Platt ML. 2006. Neural signatures of economic preferences for risk and ambiguity. *Neuron*. 49:765–775.

Izuma K, Saito DN, Sadato N. 2008. Processing of social and monetary rewards in the human striatum. *Neuron*. 58:284–294.

Jenison RL, Rangel A, Oya H, Kawasaki H, Howard MA. 2011. Value encoding in single neurons in the human amygdala during decision making. *J Neurosci*. 31:331–338.

Johnson EJ, Häubl G, Keinan A. 2007. Aspects of endowment: a query theory of value construction. *J Exp Psychol Learn Mem Cogn*. 33:461–474.

Krause K, Freund AM. 2016. It's in the means: process focus helps against procrastination in the academic context. *Motiv Emot*. 40:422–437.

Lebreton M, Bertoux M, Boutet C, Lehericy S, Dubois B, Fossati P, Pessiglione M. 2013. A critical role for the hippocampus in the valuation of imagined outcomes. *PLoS Biol*. 11: 363–367.

Lee H, Ghim J-W, Kim H, Lee D, Jung M. 2012. Hippocampal neural correlates for values of experienced events. *J Neurosci*. 32:15053–15065.

Li J, Biswal BB, Meng Y, Yang S, Duan X, Cui Q, Chen H, Liao W. 2020a. A neuromarker of individual general fluid intelligence from the white-matter functional connectome. *Transl Psychiatry*. 10:1–12.

Li J, Chen H, Fan F, Qiu J, Du L, Xiao J, Duan X, Chen H, Liao W. 2020b. White-matter functional topology: a neuromarker

for classification and prediction in unmedicated depression. *Transl Psychiatry*. 10:1–10.
Liu P, Feng T. 2018. The effect of future time perspective on procrastination: the role of parahippocampal gyrus and ventromedial prefrontal cortex. *Brain Imaging Behav*. 13:615–622.
Machado CJ, Kazama AM, Bachevalier J. 2009. Impact of amygdala, orbital frontal, or hippocampal lesions on threat avoidance and emotional reactivity in nonhuman primates. *Emotion*. 9:147–163.
Masuda A, Sano C, Zhang Q, Goto H, McHugh TJ, Fujisawa S, Itohara S. 2020. The hippocampus encodes delay and value information during delay-discounting decision making. *eLife*. 9:e52466.
Mata F, Treadway M, Kwok A, Truby H, Yücel M, Stout JC, Verdejo-Garcia A. 2017. Reduced willingness to expend effort for reward in obesity: link to adherence to a 3-month weight loss intervention. *Obesity*. 25:1676–1681.
McClure SM, Bickel WK. 2014. A dual-systems perspective on addiction: contributions from neuroimaging and cognitive training. *Ann NY Acad Sci*. 1327:62–78.
McHugh S, Campbell T, Taylor A, Rawlins J, Bannerman D. 2008. A role for dorsal and ventral hippocampus in inter-temporal choice cost-benefit decision making. *Behav Neurosci*. 122:1–8.
Mizuno K, Tanaka M, Ishii A, Tanabe HC, Onoe H, Sadato N, Watanabe Y. 2008. The neural basis of academic achievement motivation. *NeuroImage*. 42:369–378.
Murty VP, Ritchey M, Adcock RA, LaBar KS. 2010. fMRI studies of successful emotional memory encoding: a quantitative meta-analysis. *Neuropsychologia*. 48:3459–3469.
Nicholson AA, Sapru I, Densmore M, Frewen PA, Neufeld RW, Théberge J, Mckinnon MC, Lanius RA. 2016. Unique insula subregion resting-state functional connectivity with amygdala complexes in posttraumatic stress disorder and its dissociative subtype. *Psychiatry Res Neuroimaging*. 250: 61–72.
Onwuegbuzie AJ, Collins KM. 2001. Writing apprehension and academic procrastination among graduate students. *Percept Mot Skills*. 92:560–562.
Palombo DJ, Keane MM, Verfaellie M. 2015. How does the hippocampus shape decisions? *Neurobiol Learn Mem*. 125: 93–97.
Papies E, Stroebe W, Aarts H. 2007. Pleasure in the mind: restrained eating and spontaneous hedonic thoughts about food. *J Exp Soc Psychol*. 43:810–817.
Pennartz C, Ito R, Verschure P, Battaglia F, Robbins T. 2011. The hippocampal–striatal axis in learning, prediction and goal-directed behavior. *Trends Neurosci*. 34:548–559.
Peters J, Büchel C. 2010. Episodic future thinking reduces reward delay discounting through an enhancement of prefrontal-mediotemporal interactions. *Neuron*. 66:138–148.
Peters J, Büchel C. 2011. The neural mechanisms of inter-temporal decision-making: understanding variability. *Trends Cogn Sci*. 15:227–239.
Ploghaus A, Tracey I, Gati JS, Clare S, Menon RS, Matthews PM, Rawlins JN. 1999. Dissociating pain from its anticipation in the human brain. *Science*. 284:1979–1981.
Preacher KJ, Hayes AF. 2008. Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behav Res Methods*. 40:879–891.
Preuschoff K, Bossaerts P, Quartz SR. 2006. Neural differentiation of expected reward and risk in human subcortical structures. *Neuron*. 51:381–390.
Prévost C, Pessiglione M, Météreau E, Cléry-Melin M-L, Dreher J-C. 2010. Separate valuation subsystems for delay and effort decision costs. *The J Neurosci*. 30:14080–14090.
Rabinak CA, Angstadt M, Welsh RC, Kennedy A, Lyubkin M, Martis B, Phan KL. 2011. Altered amygdala resting-state functional connectivity in post-traumatic stress disorder. *Front Psychiatry*. 2:62.
Roy AK, Fudge JL, Kelly C, Perry JS, Daniele T, Carlisi C, Benson B, Castellanos FX, Milham MP, Pine DS. 2013. Intrinsic functional connectivity of amygdala-based networks in adolescent generalized anxiety disorder. *J Am Acad Child Psy*. 52:290–299.e2.
Sacco R, Bisecco A, Corbo D, Della Corte M, d'Ambrosio A, Docimo R, Gallo A, Esposito F, Esposito S, Cirillo M. 2015. Cognitive impairment and memory disorders in relapsing–remitting multiple sclerosis: the role of white matter, gray matter and hippocampus. *J Neurol*. 262:1691–1697.
Sarinopoulos I, Grupe DW, Mackiewicz KL, Herrington JD, Lor M, Steege EE, Nitschke JB. 2010. Uncertainty during anticipation modulates neural responses to aversion in human insula and amygdala. *Cereb Cortex*. 20:929–940.
Sasse LK, Peters J, Büchel C, Brassen S. 2015. Effects of prospective thinking on intertemporal choice: the role of familiarity. *Hum Brain Mapp*. 36:4210–4221.
Schlund MW, Cataldo MF. 2010. Amygdala involvement in human avoidance, escape and approach behavior. *Neuroimage*. 53:769–776.
Schultz W. 2000. Multiple reward signals in the brain. *Nat Rev Neurosci*. 1:199–207.
Seymour B, Dolan R. 2008. Emotion, decision making, and the amygdala. *Neuron*. 58:662–671.
Shadlen M, Shohamy D. 2016. Decision making and sequential sampling from memory. *Neuron*. 90:927–939.
Sirois FM, Pychyl T. 2013. Procrastination and the priority of short-term mood regulation: consequences for future self. *Soc Personal Psychol Compass*. 7:115–127.
Sirois FM. 2007. "I'll look after my health, later": a replication and extension of the procrastination–health model with community-dwelling adults. *Pers Indiv Differ*. 43: 15–26.
Sirois FM. 2015. Is procrastination a vulnerability factor for hypertension and cardiovascular disease? Testing an extension of the procrastination–health model. *J Behav Med*. 38:578–589.
Stawarczyk D, D'Argembeau A. 2015. Neural correlates of personal goal processing during episodic future thinking and mind-wandering: an ALE meta-analysis. *Hum Brain Mapp*. 36:2928–2947.
Stead R, Shanahan MJ, Neufeld RW. 2010. "I'll go to therapy, eventually": procrastination, stress and mental health. *Pers Indiv Differ*. 49:175–180.
Steel P, Ferrari J. 2013. Sex, education and procrastination: an epidemiological study of procrastinators' characteristics from a global sample. *Eur J Pers*. 27:51–58.
Steel P, Svartdal F, Thundiyil T, Brothen T. 2018. Examining procrastination across multiple goal stages: a longitudinal study of temporal motivation theory. *Front Psychol*. 9:327.
Strunk KK, Cho Y, Steele MR, Bridges SL. 2013. Development and validation of a 2× 2 model of time-related academic behavior: procrastination and timely engagement. *Learn Individ Differ*. 25:35–44.
Treadway MT, Buckholtz JW, Cowan RL, Woodward ND, Li R, Ansari MS, Baldwin RM, Schwartzman AN, Kessler RM, Zald

DH. 2012. Dopaminergic mechanisms of individual differences in human effort-based decision-making. *J Neurosci*. 32:6170–6176.

Treadway MT, Buckholtz JW, Schwartzman AN, Lambert WE, Zald DH. 2009. Worth the 'EEfRT'? The effort expenditure for rewards task as an objective measure of motivation and anhedonia. *PLoS One*. 4:e6598.

Vazdarjanova A, Cahill L, McGaugh JL. 2001. Disrupting basolateral amygdala function impairs unconditioned freezing and avoidance in rats. *Eur J Neurosci*. 14:709–718.

Wicker B, Keysers C, Plailly J, Royet JP, Gallese V, Rizzolatti G. 2003. Both of us disgusted in my insula: the common neural basis of seeing and feeling disgust. *Neuron*. 40:655–664.

Wikenheiser AM, Redish AD. 2015. Hippocampal theta sequences reflect current goals. *Nat Neurosci*. 18:289–294.

Wimmer GE, Shohamy D. 2012. Preference by association: how memory mechanisms in the hippocampus bias decisions. *Science*. 338:270–273.

Yonelinas AP, Ritchey M. 2015. The slow forgetting of emotional episodic memories: an emotional binding account. *Trends Cogn Sci*. 19:259–267.

Zhang S, Becker B, Chen Q, Feng T. 2019. Insufficient task-outcome association promotes task procrastination through a decrease of hippocampal–striatal interaction. *Hum Brain Mapp*. 40:597–607.

Zhang S, Feng T. 2020. Modeling procrastination: asymmetric decisions to act between the present and the future. *J Exp Psychol Gen*. 149:311–322.

Zhang W, Wang X, Feng T. 2016. Identifying the neural substrates of procrastination: a resting-state fMRI study. *Sci Rep*. 6:1–7.