

Defecatory urge increases cognitive control and intertemporal patience in healthy volunteers

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Abstract

Background: Past research has demonstrated that moderate urge to urinate improves inhibitory control, specifically among participants with higher behavioral inhibition sensitivity (BIS). The effect was absent when the urge exceeded intolerable level. The present research examines whether rectal distension-induced urge to defecate has similar effects.

Methods: The moderate and high defecatory urge were induced by rectal distension in healthy volunteers ($n = 35$), while they completed Stroop task and monetary delay discounting task. The difference of average reaction time between incongruent and congruent trials in the Stroop task (Stroop interference) and the preference for larger-later rewards in the delay discounting task were the primary outcomes.

Key Results: Participants with high BIS ($n = 17$) showed greater ability to inhibit their automatic response tendencies, as indexed by their Stroop interference, under moderate urge relative to no urge (128 ± 41 ms vs 202 ± 37 ms, $t_{64} = 2.07$; $P = 0.021$, Cohen's d : 0.44), but not relative to high urge (154 ± 45 ms, $t_{64} = 1.20$; $P = 0.12$, Cohen's d : 0.30). High BIS participants also showed a higher preference for larger-later reward in the delay discounting task under high (odds ratio = 1.51 [1.02-2.25], $P = 0.039$) relative to no urge, but not relative to moderate urge (odds ratio = 1.02 [0.73-1.42], $P = 0.91$). In contrast, rectal distension did not influence performance on either of the tasks in participants with low BIS ($n = 18$).

Abbreviations: AIC, Akaike's information criterion; aMCC, anterior midcingulate cortex; BAS, behavioral activation system; BIS, behavioral inhibition system; IBS, irritable bowel syndrome; MDP, minimal distending pressure; mPFC, medial prefrontal cortex; pACC, pregenual anterior cingulate cortex; RT, reaction time; VAS, visual analogue scale.

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Warlop and Van Oudenhove equally contributed as last author.

Conclusions and inference: These findings may be interpreted as a “spill-over” effect of inhibition of the urge to defecate to volitional cognitive control among healthy participants with high BIS.

KEYWORDS

defecatory urge, gut-brain axis, inhibitory control, rectal barostat

1 | INTRODUCTION

Inhibitory control refers to one's ability to restrain and override impulses to achieve goals of higher importance or with better payoffs.^{1,2} A growing body of literature highlights the existence of a common, domain-independent capacity for inhibitory control.^{3,4} Specifically, when inhibitory control is activated in one domain, it can facilitate control in other (unrelated) domains. For instance, controlling the urge to urinate facilitates inhibitory control in cognitive domains, specifically in tasks requiring impulse inhibition.² It has been proposed that inhibitory control processes across different domains share common neurological pathways,⁵ involving brain regions along the cingulate sulcus, with dopamine being the key neurotransmitter.^{6,7}

Neurological processes underlying rectal filling are in many ways similar to bladder control processes.^{5,8-10} Consequently, in the present research, we propose that defecatory urge should also facilitate inhibitory control. We explore this hypothesis across two self-regulatory tasks by examining the interplay between rectal urge conditions of varying degrees and individuals' chronic differences in behavioral inhibition sensitivity (BIS).¹¹ Specifically, we hypothesized that, for people with high BIS, experiencing defecatory urge, relative to no urge, should improve performance on tasks that require inhibitory control. Past research shows that increased urination urge reportedly enhanced inhibitory control only among individuals with high BIS sensitivity.² This is consistent with reinforcement sensitivity theory^{12,13} which argues that BIS fosters inhibition of prepotent conflicting behaviors and facilitate self-regulation. Therefore, we expected the positive consequences of controlling defecatory urge on self-regulation to be limited to participants with high BIS.

Following past research, we chose the Stroop task and delay discounting task to measure inhibitory control.¹⁴ In particular, the Stroop task¹⁵ is a robust and well-established method to measure cognitive control. It measures people's ability to disregard distractions and override impulses in the service of task performance.^{16,17} Moreover, delay discounting measures one's ability to resist immediate temptations and to wait for larger-later rewards, signifying patience, and self-control. Both of these tasks are commonly used as measures of inhibitory control.

Finally, we used rectal distension technique (barostat) to induce varying levels of defecatory urge. This is a widely used technique, which enables induction of rectal sensation in a systematic and intensity-controlled manner. This is important because while past

Key Points

- Defecatory urge improves inhibitory control in healthy volunteers.
- Inhibition of the urge to defecate facilitated cognitive control under moderate urge, and increased preference for larger-later rewards in the delay discounting task under high urge, among healthy humans with high behavioral inhibition sensitivity (BIS), but not among those with low BIS.
- These results demonstrate that mechanical signals originating in the rectum that require inhibition can improve inhibitory control in other domains, and contribute to studies on cognitive function in functional GI disorders.

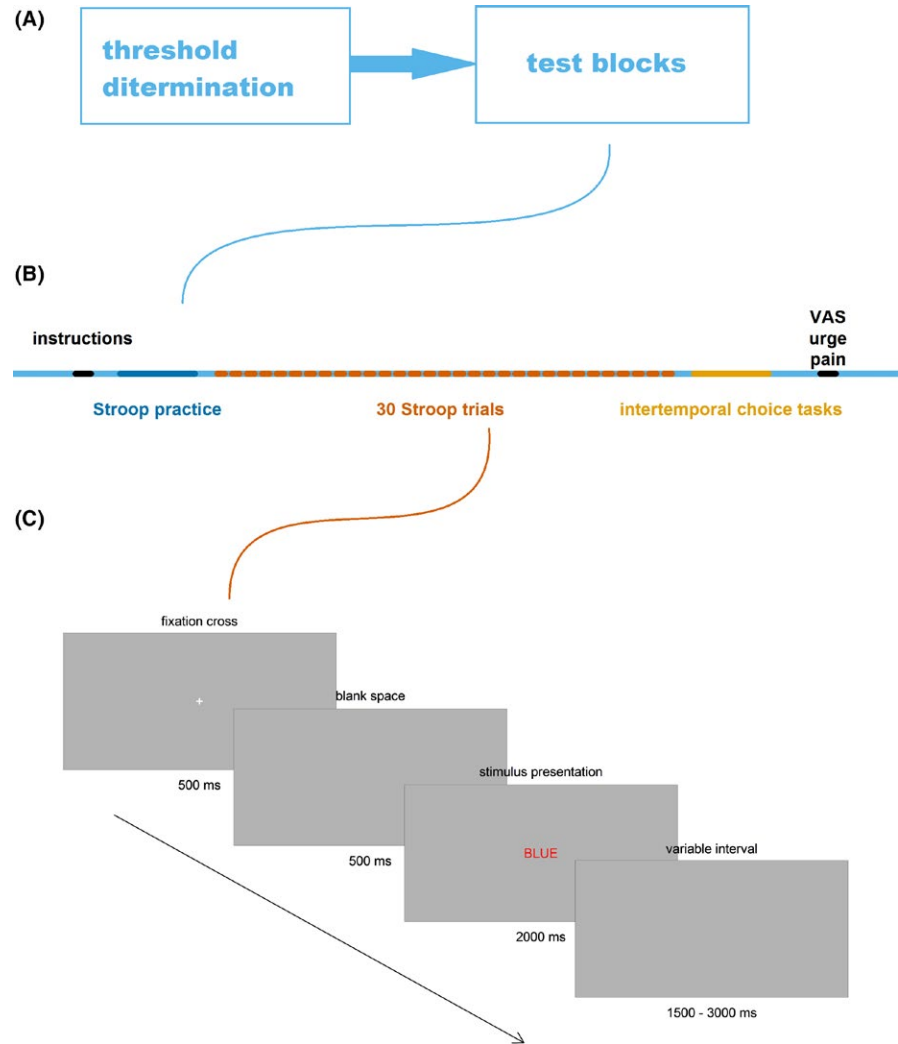
research on bladder filling has found that inhibition of urination urge facilitates cognitive control,² other findings suggest that extreme urination urge may impair cognitive functioning.¹⁸ Using a controlled rectal distension method, therefore, enables us to test our hypothesis across different levels of defecatory urge (eg, no, medium, and high urge) and to explicate potential boundaries of our hypothesis.

2 | MATERIALS AND METHODS

2.1 | Participants

Healthy male, and non-pregnant, non-breastfeeding female participants, aged 18-60 years old at the time of consent, were recruited in this randomized, counterbalanced, single-blinded mechanistic interventional crossover study. Candidates with color blindness or those who used any medication or drugs (except contraceptive pills) were excluded. All study visits were conducted in the endoscopy unit, at University Hospital Gasthuisberg of the KU Leuven. The sample size was calculated based on the previous findings² showing a medium-sized effect of moderate urinary urge on Stroop performance in high BIS participants (one-tailed paired *t* test, alpha = 0.05, Cohen's *d* = 0.50, power = 85%). Last menstrual period from female volunteers was recorded during screening, and all study visits were scheduled during the follicular phase. A schematic overview of the study is presented in Figure 1.

FIGURE 1 Schematic overview of the experimental procedure. (A) overview of a study visit: firstly, a threshold determination involving a stepwise distension session was undertaken, followed by tonic distension blocks to ensure that the stimulus length would allow stable pressure, volumes, and ratings of moderate/high urge. Finally, three test blocks were performed (one for each level of urge) in a counterbalanced order. (B) overview of a test block: firstly, instructions were provided, and a Stroop practice session was undertaken, followed by 30 Stroop trials in a randomized order, followed by five delay discounting tasks. At the end of each test block, retrospective ratings of urge and pain were collected using visual analogue scales (VAS). (C) an example of a Stroop trial: presented in the following sequence: a fixation cross displayed 500 ms, followed by a blank space for 500 ms, followed by stimulus presentation for 2000 ms, followed by an intertrial blank space whose display time varied between 1500 and 3000 ms (uniform distribution) until the next trial



2.2 | Ethical approval and clinical trial registration

The study was approved by the Medical Ethics Committee of the University Hospitals Leuven; Belgium (ML10139, 17 Aug 2014), preregistered at ClinicalTrials.gov (NCT02043561: <https://clinicaltrials.gov/>, 23 Jan 2014), and performed in accordance with the Declaration of Helsinki, including written informed consent.

2.3 | Behavioral Inhibition Sensitivity

The Behavioral Inhibition Sensitivity/Behavioral Activation Sensitivity scale (BIS/BAS)¹¹ was administered together with screening questionnaires before participants' visit to the laboratory. Participants were divided into two groups (high BIS group vs low BIS group) based on a median split on the BIS scale to test our hypothesis that the effect of urge inhibition would occur in high BIS participants only.

2.4 | Distending device

Rectal distensions were induced by an intrarectal balloon (600 mL capacity) and controlled by an electronic barostat (Dual Drive

Barostat, Distender Series II; G&J Electronics Inc). A personal computer running custom-made software provided by the manufacturer (Protocol Plus, G&J Electronics Inc) was used to program the barostat and to record the intraballoon pressure and volume continuously.

2.5 | Preparation

Following an overnight fast and rectal cleansing with tap water enema, a finely folded balloon was introduced into the participants' rectum with the caudal end 6 cm from the anal verge and then connected to the barostat device. Participants were placed in a semi-recumbent position on a bed. The balloon was then unfolded by inflation with 150 mL of air and after that completely deflated.

2.6 | Threshold determination

The minimal distending pressure (MDP) was first determined, as the pressure level at which respiratory fluctuations were regularly recorded. To determine the individual threshold for defecatory urge,

a stepwise pressure-controlled distension procedure (steps of 4 mm Hg/30 s) starting from MDP was performed,^{19,20} following a 15-minute accommodation period. After 15 seconds into each distension step, participants rated their perceived intensity of defecatory urge and pain, using a 100-mm visual analogue scale (VAS) ranging from “no urge” to “maximal urge” and “no pain” to “maximal pain” on a computer screen. The stepwise distension procedure was ended when either the participants reported maximal urge (100 on the VAS) or an intraballloon volume of 500 mL was achieved.

Three pressure thresholds were derived from this stepwise distension sequence²⁰ and were used during the subsequent parts of the study:

1. No urge (balloon deflated)
2. Moderate urge (first pressure step evoking a score of 41 or more on the urge VAS)
3. High urge (first pressure step evoking a score of 81 or more on the urge VAS)

After the stepwise distension, participants went through three tonic distension blocks, in which they were exposed to tonic distension at no urge, moderate urge, and high urge pressure thresholds (in counterbalanced order) for 180 seconds and were asked to rate their urge and pain sensations on a VAS every 30 seconds (to ensure that this stimulus length would allow us to achieve stable pressures, volumes, and above all ratings of moderate/high urge).

2.7 | Test blocks

Between the threshold determination and the test blocks, participants rested in bed for 10 minutes while the rectal balloon was not extubated. During each test block, rectal distension at one of the three individually titrated pressure thresholds, described above, was administered in counterbalanced order, with a 10-minute break in between. During each block, participants performed the Stroop task followed by the delay discounting task. At the end of each block, all participants rated VAS for urge and pain retrospectively.

2.7.1 | Stroop task

The Stroop task requires participants to indicate the font color of a series of visually presented color words as quickly as possible. In *incongruent* trials, participants should ignore the meaning of the color word, thus override their dominant and impulsive response tendencies, and attend to its font color instead. Stroop performance is assessed by calculating the difference between the average response latencies in incongruent and congruent trials, an index referred to as *Stroop interference*. A smaller Stroop interference score, therefore, indicates greater cognitive ability to disregard distractions and impulses and to stay focused on the goal.

The Stroop task consisted of three types of trials²¹: the “word naming” trials in which the color words (eg, the word RED) were displayed in black font, and the “incongruent” trials (eg, the word RED

in blue font) and the “congruent” trials (eg, the word RED in red font) in which the color words were displayed in colors. For congruent and incongruent stimuli, participants were instructed to neglect the meaning of the word, but only respond to the font color of the displayed stimuli. To respond across these trials, participants pressed one of three keys on a keyboard labeled with colors red, blue, or green that corresponded to the word color (ie, in the word-naming trials) or the font color (ie, in the congruent and incongruent trials) of the stimuli.

A Stroop trial consisted of the following sequence: a fixation cross for 500 ms, followed by a blank space for 500 ms, and stimulus presentation for 2000 ms. The intertrial intervals were uniformly distributed between 1500 and 3000 ms. Responses were recorded between the start of stimulus presentation until 1500 ms into the intertrial interval; the stimulus disappeared from the screen as soon as the response was registered. Any response faster than 150 ms was considered abnormal and hence removed before the analysis. For each participant, the average reaction time for each trial type (ie, congruent, incongruent, and word naming) was then calculated. As mentioned earlier, the main dependent variable was Stroop interference which was calculated by subtracting average response times in congruent trials from the average response time in incongruent trials for each participant.

At the beginning of the experiment, participants went through one practice block in which the three trial types were presented with instructions. During the practice block, stimuli from the three trial types were presented in a fixed order: word naming, congruent, and incongruent. Afterward, at each distension level, participants performed a block of 30 Stroop trials, consisting of 10 trials of each type. The 30 trials at each distension pressure level were presented in a random order, and no feedback was provided. However, the practice block would repeat until participants responded to all 30 stimuli correctly. Colors were counterbalanced between trial blocks. Presentations were therefore unblocked and uncued within each trial block to ensure the maximal experience of conflict.

2.7.2 | Delay Discounting Task

Immediately after each Stroop trial, participants performed a delay discounting task, consisting of five intertemporal monetary choices.²² For each choice, participants indicated their preference for either a smaller, sooner or a larger, later monetary reward²² (eg, “Would you prefer 24 euro now or 35 euro in 29 days?”). Participants pressed button “1” on the keyboard to choose the immediate but smaller amount, and “2” to choose the larger but delayed amount. Participants’ choices were then treated as binary outcomes in a logistic regression model. Overall, participants’ tendency to choose larger, later rewards over smaller, sooner rewards signifies their ability to resist immediate temptations and to wait for larger rewards in the future, a critical capacity for self-regulation.

In the informed consent form, and upon completion of the three test blocks, all participants signed a document indicating that they

would be awarded a fixed amount of money after completing the experiment.

2.8 | Statistical analysis

All statistical analysis was done using SAS Version 9.4 (SAS Institute, Cary, NC, USA). Reaction times of the Stroop test were reported as mean \pm SEM. Differences were considered significant when $P \leq 0.05$. The variance-covariance structure providing the best fit was chosen based on the minimum value of Akaike's Information Criterion (AIC).

For each participant, response latencies within each Stroop condition (ie, congruent, incongruent, and word naming) were prepared in each test block using trimming methods²³ and subsequently averaged. Specifically, for each participant, all the erroneous responses, responses faster than 150 ms, and any responses 3 SD above or below the mean of the participant's response latencies per Stroop and urge condition were removed prior to calculating average response latencies. The remaining data were then averaged for each urge and Stroop condition, for each participant. The preprocessed Stroop color-naming data were then analyzed in a 3 (urge condition) \times 3 (Stroop condition) within-subject mixed model including the urge condition-by-Stroop condition interaction effect in each BIS group separately, with the order of the test blocks, and the subjective pain rating added as covariates. Lower-tailed planned t-contrasts were performed to test our hypotheses that Stroop interference—the difference between average response latencies between incongruent and congruent trials—decreases under moderate (but not under high urge), compared to no urge condition, in the high BIS group, but not in the low BIS group. To examine the potential effect of urge condition on response latencies in general (ie, not related to inhibitory processes), response latencies in the Stroop word-naming condition were also analyzed in a separate mixed model. Specifically, two-tailed planned t-contrasts were performed to test our hypothesis that response latencies in the Stroop word-naming trials did not vary as a function of the urge for each BIS condition.

Participants' choice between a larger, later reward and a smaller, immediate reward in the delay discounting task was treated as a binary dependent variable in a generalized linear mixed model with urge condition as a within-subject factor, and order of the test block and subjective pain rating as covariates,²⁴ in each BIS group separately. The probability of choosing a larger-later reward was further compared in high vs no urge condition, and moderate vs no urge condition for each BIS group.

3 | RESULTS

3.1 | Participants

Thirty-five healthy volunteers [23 (66%) women, age: 22 ± 0.3 years, recruited between September 10, 2014 and September 3, 2015] participated in the study (Supplementary Figure S1). Participants were divided into high ($n = 17$) and low ($n = 18$) BIS groups, based on a median split of their BIS score (median [IQR] 22 [18, 23]). Four female volunteers in the low BIS group and one in the high BIS group self-reportedly took contraceptive pills. This proportion did not differ between high and low BIS groups (Fisher exact test $P = 0.16$). The demographic characteristics of the participants are presented in Table 1. All participants completed the study, and there was no adverse event reported throughout the experiment. The overall error rate in the Stroop task was 2.32%, and all participants completed the Stroop task with more than 90% correct answers. Therefore, no participant was excluded for making too many errors. Table 2 shows the overall error rates in the Stroop task in each urge condition. Further, statistical analysis was also performed on Stroop interference including the number of errors as a covariate, but the main outcomes did not change.

3.2 | Manipulation check

Personalized distension pressures (moderate urge: 29.6 ± 1.2 mm Hg, high urge: 41.6 ± 1.1 mm Hg) were determined according to each participant's average subjective urge ratings on a 100-mm scale. The average retrospective urge ratings, measured at the end of each test block, were significantly higher in the moderate (41.0 ± 3.3 mm) and high (67.2 ± 4.2 mm) urge conditions compared to the no urge condition (20.0 ± 3.3 mm), as shown in Figure 2A (main effect of urge condition, $F_{2,34} = 52.65$, $P < 0.0001$, planned contrast: moderate urge vs no urge, $t_{34} = 5.08$, $p_{\text{Holm}} < 0.0001$, high urge vs no urge, $t_{34} = 9.48$, $p_{\text{Holm}} < 0.0001$, high urge vs moderate urge, $t_{34} = 7.82$, $p_{\text{Holm}} < 0.0001$). These results confirm that our urge manipulation was successful and worked as intended.

Similarly, retrospective pain ratings, measured at the end of each test block, were significantly higher in the high urge (27.3 ± 4.9 mm) compared to the no urge (5.4 ± 1.7 mm) condition. However, no difference between the moderate urge (11 ± 2.9 mm) and no urge conditions was found (main effect of urge condition, $F_{2,34} = 14.76$, $P < 0.0001$, planned contrast, moderate vs no urge, $t_{34} = 1.90$, $p_{\text{Holm}} = 0.15$, high vs no urge, $t_{34} = 5.39$, $p_{\text{Holm}} < 0.0001$, high vs moderate urge, $t_{34} = 4.50$, $p_{\text{Holm}} = 0.0002$), as shown in Figure 2B. Given

TABLE 1 Demographic characteristics of participants

	High BIS group	Low BIS group		P value
Gender (F/M)	12/5	11/7	$\chi^2 = 0.097$	0.76
Age (y)	23.5 ± 1.4	22.2 ± 0.4	$t = 0.84$	0.41
BIS score	23.7 ± 0.4 [range: 22,28]	18.4 ± 0.4 [range: 16,21]	$t = 9.18$	<0.0001

the differences in pain ratings between the high urge and the other conditions, we controlled for pain ratings in all subsequent analyses.

3.3 | Stroop interference

3.3.1 | High BIS group

The personalized distension pressures were not associated with participants' Stroop interference in high BIS group ($P > 0.05$). Consistent with our hypothesis, the Stroop interference was significantly smaller in the moderate urge condition compared to the no urge condition (planned contrast, lower tailed, moderate urge 128 ± 41 ms vs no urge 202 ± 37 ms, $t_{64} = 2.07$; $p_{\text{Holm}} = 0.021$, Cohen's $d: 0.44$), indicating that moderate urge improves inhibitory control. However, we did not find a difference in Stroop interference between the high urge and no urge conditions (planned contrast, lower tailed, high urge 154 ± 45 ms vs no urge 202 ± 37 ms, $t_{64} = 1.20$, $p_{\text{Holm}} = 0.12$, Cohen's $d: 0.30$).

TABLE 2 Error rate of Stroop tasks in each Stroop type in each urge condition

Urge condition	Stroop type		
	Incongruent	Congruent	Word naming
No urge	4.29%	0.86%	2.57%
Moderate urge	2.28%	1.14%	2.28%
High urge	4.86%	0.57%	1.71%

Note. Error rate was higher in the incongruent trials compared to congruent or word-naming trials. Further, the error rate did not differ between urge conditions. (Friedman's chi-square test, Stroop type: $Q = 17.6$ $P = 0.0001$, Urge condition: $Q = 1.69$ $P = 0.43$).

3.3.2 | Low BIS group

The personalized distension pressures were not associated with participants' Stroop interference in low BIS group ($P > 0.05$). Consistent with our hypothesis, urge condition did not influence cognitive control among people with low BIS. Specifically, we did not find significant differences, neither between the moderate urge and no urge conditions (planned contrast, lower tail, moderate urge 158 ± 32 ms vs no urge 168 ± 24 ms, $t_{68} = 0.34$ $p_{\text{Holm}} = 0.37$, Cohen's $d: 0.08$), nor between the high urge and no urge conditions (planned contrast, high urge 178 ± 27 ms vs no urge 168 ± 24 ms, $t_{68} = 0.72$ $p_{\text{Holm}} = 0.76$, Cohen's $d: 0.17$).

Figure 3 shows the Stroop interference scores as a function of urge conditions in both the high and the low BIS group.

Together, these results are consistent with our hypothesis that moderate defecatory urge improves inhibitory control ability only in people with high BIS.

3.4 | Stroop word naming

Contrary to the Stroop color-naming trials, the Stroop word-naming trials consisted of color words (eg, the words, RED, BLUE, and GREEN) displayed in black font. Specifically, in these trials, participants reacted only to the words, instead of font color. As expected, there was no effect of urge on response latencies in this word-naming task, which did not require conflict resolution (planned contrasts, two-tailed, high BIS group: moderate vs no urge $t_{68} = 0.49$ $p_{\text{Holm}} = 0.63$ Cohen's $d: 0.12$, high vs no urge $t_{68} = 0.81$ $P = 0.42$ Cohen's $d: 0.20$; low BIS group: moderate vs no urge $t_{68} = 1.04$ $p_{\text{Holm}} = 0.30$ Cohen's $d: 0.25$, high vs no urge $t_{68} = 0.76$ $p_{\text{Holm}} = 0.45$ Cohen's $d: 0.18$).

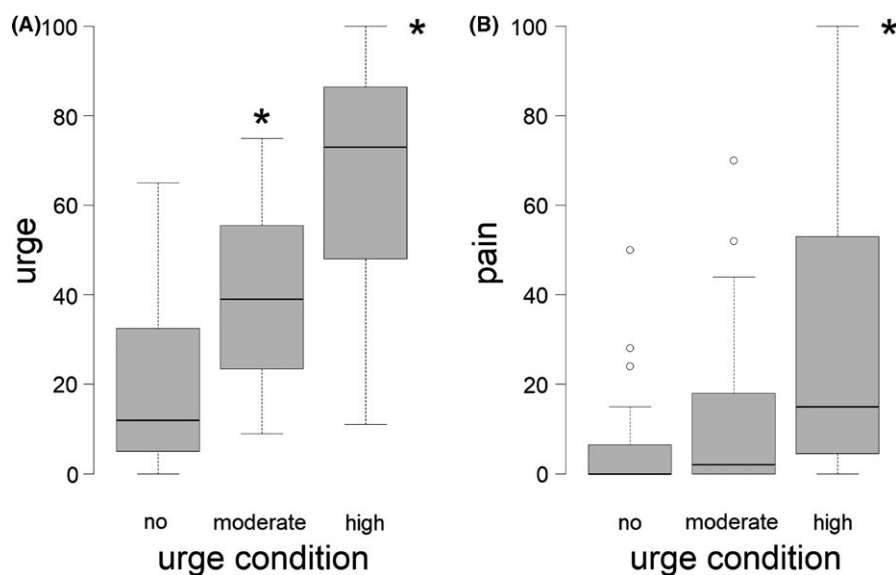


FIGURE 2 Rectal barostat successfully induced defecatory urge in both moderate and high urge conditions. Average VAS (A) urge scores in high and moderate urge conditions were significantly higher than in no urge condition ($*P < 0.05$), and average VAS (B) pain scores in high urge condition was higher than in no urge condition ($*P < 0.05$). VAS, visual analogue scale (0-100 mm)

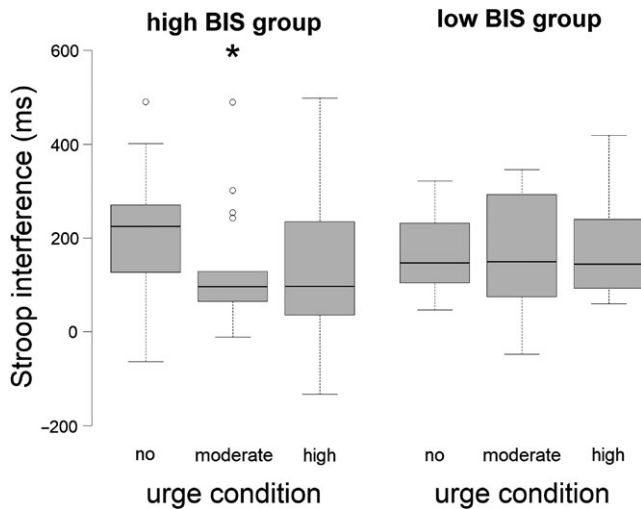


FIGURE 3 Stroop interference was smaller under moderate (but not high) urge condition, both compared to no urge condition, in the high BIS group ($*P < 0.05$). The Stroop interference was not predicted by urge conditions in the low BIS group

3.5 | Delay discounting task

3.5.1 | High BIS group

As shown in Figure 4, participants preferred the larger-later reward more frequently under high urge compared to no urge ($z = 2.06$, $P = 0.039$, odds ratio = 1.51, 95% CI: 1.02-2.25). However, participants' preference under moderate urge was not significantly different from their preference in the no urge condition ($z = 0.11$, $P = 0.91$, odds ratio = 1.02, 95% CI: 0.73-1.42). Overall, these results suggest that increased levels of urge render more patience in intertemporal choices, among people with high BIS.

3.5.2 | Low BIS group

As expected, urge conditions did not predict patience in intertemporal choices among participants with low BIS. Specifically, participants' preference under high urge was not significantly different from no urge ($z = -1.61$, $P = 0.11$, odds ratio = 0.67, 95% CI: 0.42-1.09), nor did their preference differ significantly between the moderate urge and no urge conditions ($z = -0.21$, $P = 0.83$, odds ratio = 0.93, 95% CI: 0.50-1.75), as shown in Figure 4.

4 | DISCUSSION

Building on past findings suggesting the existence of a common, domain-independent inhibitory control system, we hypothesized and provided empirical evidence that inhibition of defecatory urge facilitates inhibitory control, across both cognitive and financial decision-making (ie, increased patience in the delay discounting) domains, among individuals with high BIS.

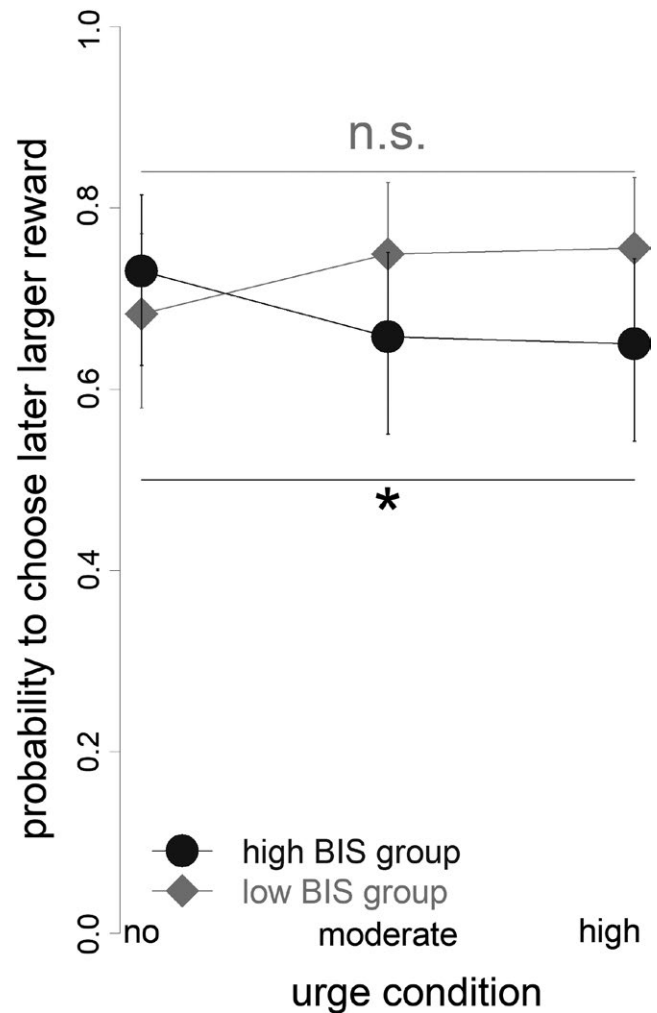


FIGURE 4 The probability that participants chose a larger-later reward, and thus show more patience, in the delay discounting task was higher under the high (but not moderate) urge condition, both compared to no urge condition, in the high BIS group ($*P < 0.05$). Among participants with low BIS, urge condition did not significantly predict the choice of larger-later rewards

Particularly, our findings demonstrate that among participants with high BIS, moderate (but not high) urge significantly reduced Stroop interference, compared to a no urge condition. In other words, high BIS participants showed improved ability in inhibiting their automatic response tendencies under moderate defecatory urge induced by the rectal balloon. Moreover, we found that high BIS participants also showed more patience in the intertemporal monetary choices under high (but not moderate) urge, relative to no urge. Furthermore, in line with our reasoning, among individuals with low BIS, increased defecatory urge did not correspond to enhancement in the Stroop performance, nor did it increase patience in the delay discounting task. Overall, our findings are consistent with the inhibitory "spill-over" effect that was found earlier under an increased urge to urinate among the high BIS individuals.²

While our findings are consistent with the existence of a domain-general inhibitory control system, further research is necessary for

explicating the neurological underpinnings of this system. From a neurological perspective, the anterior midcingulate cortex (aMCC) and adjacent pregenual anterior cingulate cortex (pACC) may be central to the inhibitory "spill-over" effects, given their important role in conflict detection.^{5,25} For example, pACC^{26,27} responds differentially to incongruent trials (ie, when the font color mismatches the word meaning) compared to congruent trials in the Stroop task, and those differential responses further extend to the posterior cingulate cortex. Moreover, the adjacent regions along the cingulate sulcus implement a domain-general inhibitory control process,²⁸ and overlap partly with representations of other functions, such as pain, on the border between the aMCC and posterior midcingulate cortex.²⁹ Importantly, a meta-analysis by Tillisch et al³⁰ revealed that the pACC and the aMCC were also activated in response to rectal balloon distension in healthy controls. It is, however, noteworthy that Tillisch et al focused on a very different research question, and designs of studies included in their meta-analysis were not identical to the present study. We, therefore, could only speculate which brain regions may be involved in the effects found in our study. It will be important to replicate the current findings using brain imaging techniques.

Furthermore, Amodio et al found a correlation between participants' BIS and pACC/aMCC responses to error detection in an electroencephalography study.³¹ More specifically, participants with higher BIS had stronger responses in the adjacent area between the pACC and aMCC when they performed a No-Go task, in which they were requested NOT to respond to a certain cue.³¹ In our study, the Stroop task, like the No-Go task, also required participants to inhibit their impulsive response tendencies. This might explain the differential effects in the high BIS and low BIS groups in our study. Putting the evidence together, we propose that the brain responses to rectal filling and inhibitory control overlap in the adjacent cingulate subregions including pACC and aMCC, and that response in these areas are moderated by BIS. These regions may serve as an integrative center that mediated the "spill-over" effect observed in our study.

The delay discounting task consists of a series of choices between a smaller-sooner monetary reward and a larger-later reward. Therefore, the task is often used to measure the ability to control impulsiveness to maximize future outcomes. While Stroop performance and delay discounting both tap into self-regulation ability, and both are improved when people simultaneously control the urge to void,² our findings suggest that the response to these tasks seems to be moderated by different levels of defecatory urge. Recent work has also found other dissociations between these tasks.³² Indeed, in the delay discounting task, brain regions that are related to self-regulation and inhibition were activated when participants made an impulsive choice, including the medial orbital frontal cortex, and medial prefrontal cortex (mPFC),^{1,14} but not including the abovementioned pACC or the aMCC, which are associated with inhibitory control. Further research needs to examine exactly why different tasks are differentially sensitive to urge level. One crucial difference might be that resisting to the lure of immediate financial rewards, and to wait for later large rewards, is a higher order "self-control" task which not

only depends on people's ability to inhibit impulses but also depends on their subjective processing of delay times.^{33,34} Therefore, in contrast to the Stroop task, a delay discounting task might involve multiple cognitive operations,¹ and is subject to individual differences in relative salience of saving and spending goals.

Another consideration is that the high urge condition was accompanied by increased pain experience, relative to the two other conditions. Pain could interrupt attention,³⁵ and might do so more in a basic cognitive control task (eg, the Stroop task), compared to when people try to exert higher order, motivated, self-control (eg, in intertemporal choices). Notably, we used pain ratings as a covariate in all of our analysis, and it did not significantly influence any of the major outcomes. In addition to the effect induced by pain, extremely high urge might also undermine cognitive control. Although we did not extend our investigation to extreme, unbearable, high urges, prior research has found decrements in cognitive performance when the urge (to urinate) increased to a very high, unbearable, level.¹⁸ It is however noteworthy that the prior research had a small sample size ($n = 8$). Therefore, further investigation is necessary to confirm the differential cognitive responses to moderate and extremely high physiological urge conditions.

There are a few limitations to the current study. Firstly, the anticipation of visceral pain may influence inhibitory control. Therefore, we tried to minimize the effect of pain (and hence its anticipation) in our study design. Most of the volunteers reported no or minimal pain during distension, but some of them did. Hence, we controlled for pain ratings in our analyses. Further, we counterbalanced the order of distensions conditions in both tonic distension blocks and test blocks to minimize predictability. However, given the uncertainty about the order of distension intensities, we cannot completely rule out anticipatory effects, especially as we did not include ratings of anticipatory fear. Secondly, we limited our participants to the healthy normal weight population and did not include patients with functional bowel disorders such as irritable bowel syndrome (IBS), which is currently viewed as caused by dysregulation of the "brain-gut axis."³⁶ Moreover, patients with IBS have shown increased sensitivity^{37,38} to rectal distension compared to normal controls, both in terms of urge and pain thresholds. Therefore, it would be interesting to investigate inhibitory control responses to different levels of rectal distension above and below the urge threshold of patients with IBS.

In summary, we found that inhibition of the urge to defecate facilitated inhibitory control and rendered more patience in the delay discounting task, among healthy humans with high BIS sensitivity. These findings have the potential to improve our understanding of the nature of different volitional cognitive control processes and their interaction.

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DISCLOSURES

The authors have nothing to disclose.

AUTHOR CONTRIBUTIONS

DZ, MC, NW, MM-J, MT, LW, and LVO designed the research; DZ and MC collected the data; DZ, MM-J, and LVO analyzed data and performed statistical analyses; DZ, MM-J, and LVO wrote the manuscript. MM-J, LW, JT, and MC revised the manuscript. LVO and LW had primary responsibility for the final content. All authors read and approved the final manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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