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A Test of the Behavioral Model of Tic Disorders Using a Dynamical Systems Framework

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Tic disorders are a class of neurodevelopmental disorders characterized by involuntary motor and/or vocal tics. It has been hypothesized that tics function to reduce aversive premonitory urges (i.e., negative reinforcement) and that suppression-based behavioral interventions such as habit reversal training (HRT) and exposure and response prevention (ERP) disrupt this process and facilitate urge reduction through habituation. However, previous findings regarding the negative reinforcement hypothesis and the effect of suppression on the urge-tic relationship have been inconsistent. The present study applied a dynamical systems framework and within-subject time-series autoregressive models to examine the temporal dynamics of urges and tics and assess whether their relationship changes over time. Eleven adults with tic disorders provided continuous urge ratings during separate conditions in which they were instructed to tic freely or to suppress tics. During the free-to-tic conditions, there was considerable heterogeneity across participants in whether and how the urge-tic relationship followed a pattern consistent with the automatic negative reinforcement hypothesis. Further, little evidence for within-session habituation was seen; tic suppression did not result in a reduction in premonitory urges for most participants. Analysis of broader urge change metrics did show significant disruption to the urge pattern during suppression, which has implications for the current biobehavioral model of tics.

Keywords: Tourette syndrome; tics; behavior therapy; habituation; negative reinforcement; systems theory

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Persistent tic disorders (PTDs; including Tourette Disorder) are a class of neurodevelopmental disorders characterized by rapid, repetitive, nonrhythmic involuntary movements and/or vocalizations (i.e., motor and vocal tics; American Psychiatric Association [APA], 2013). Although tics are involuntary, most individuals can temporarily suppress them with sustained concentration and effort (Conelea et al., 2018). Many individuals also report that their tics are immediately preceded by unpleasant premonitory urges that signal the imminence of a tic and are temporarily alleviated when tics are executed (Banaschewski et al., 2003; Crossley et al., 2014; Woods et al., 2005).

Although the exact cause of tics remains unclear, converging evidence strongly suggests that they are the result of dopaminergic dysfunction within the cortico-striatal-thalamo-cortical (CSTC) pathways involved in the selection and execution of actions (Buse et al., 2013). Additionally, several studies have shown that internal and external behavioral processes influence the occurrence and expression of tics (Capriotti et al., 2014; Essoe et al., 2021; Evers & Van de Wetering, 1994; Himle et al., 2014). Specifically, it has been proposed that tic execution results in a contingent and immediate reduction in premonitory urges, strengthening tics through automatic negative reinforcement (Crossley et al., 2014; Himle et al., 2007; Kwak et al., 2003).

Several studies have reported findings generally consistent with the automatic negative reinforcement hypothesis. Specht et al. (2014) compared premonitory urge ratings and tic occurrence across consecutive 10-second intervals during periods of free-to-tic (FTT) and reinforced tic suppression (TSUP) and found that higher urge ratings predicted an increased likelihood of tics occurring in immediately subsequent intervals in the FTT condition. Likewise, Brandt et al. (2016) asked 17 participants with PTDs to continuously rate their urges in real time and found that, on average, urge ratings increased in the 10 seconds immediately before tic occurrence and decreased in the 10 seconds following the tic. Using similar methodology, Schubert et al. (2021) found that higher urge ratings predicted an increased probability of engaging in a tic, and that urges were stronger while a tic was occurring. Finally, Capriotti et al. (2014) interspersed participant-initiated 10-second FTT pauses throughout a TSUP condition and found that tics were more frequent, and urges were lower, during FTT compared to TSUP.

Behavioral interventions for PTDs, such as habit reversal training (HRT; Azrin & Nunn, 1973) and an adapted version of exposure and response prevention (ERP; Hoogduin et al., 1997), are evidence-based suppression-based treatments (McGuire et al., 2014). During HRT, individuals are taught to recognize discrete instances of a specific tic and then to interrupt or prevent tic occurrence by engaging in a response that is incompatible with the tic (i.e., a competing response, CR; Woods et al., 2008) until the urge to tic subsides (i.e., until within-trial habituation occurs). Likewise, during ERP, individuals are taught to suppress their tics while tolerating and tracking premonitory urges, with the assumption that the urge will subside (Verdellen et al., 2004). Although the exact mechanism(s) underlying HRT and ERP are not clear, the prevailing hypothesis is that tic suppression disrupts the negatively reinforced urge-tic cycle and facilitates within- and between-session habituation to the urge (Hoogduin et al., 1997). Habituation is a form of nonassociative learning in which an organism's response to a stimulus decreases due to repeated or prolonged stimulus presentation (Groves & Thompson, 1970). Prior research has shown that habituation can occur both in the short term as a moment-by-moment decrease in the response (i.e., within-session habituation) and in the long term as evidenced by decreased responding across repeated trials (i.e., between-session habituation; see Groves & Thompson, 1970, for a review).

To examine between-session urge reduction, Houghton et al. (2017) examined pre- and post-intervention urge severity in a large sample of children and adults who were deemed treatment responders following a standardized course of Comprehensive Behavioral Intervention for Tics (CBIT; for which HRT is a primary component; Piacentini et al., 2010; Wilhelm et al., 2012). Results showed no evidence of between-session urge reduction; even though tic severity decreased following treatment, scores on the Premonitory Urge for Tics Scale (PUTS; Woods et al., 2005) did not.

Within-session habituation has not been directly tested during HRT, and indirect evidence is minimal. Verdellen et al. (2008) did find both within- and between-session reductions in general urge intensity over the course of 10, 2-hour sessions of suppression in the context of ERP (where urge reduction was the focus of the sessions). In contrast, Specht et al. (2013) examined within-session habituation by mapping premonitory urge change across a single 40-minute period of TSUP and failed to find an overall reduction in urges (i.e., within-session habituation; Specht et al., 2013). As a notable comparison, anxiety habituation in the context of ERP for obsessive-compulsive disorder has consistently been found to occur well within a 40-minute time period (e.g., Benito et al., 2018). Finally, studies comparing within-session premonitory urge ratings during alternating periods of FTT and TSUP have also generally failed to find differences in urge rating between these two conditions (Capriotti et al., 2012; Capriotti et al., 2014; Himle et al., 2007).

Although recent research has cast doubt on whether urge habituation occurs within- or between-session, extant studies have methodological limitations that may contribute to the inconsistent results observed. First, prior studies have largely evaluated the urge-tic relationship and urge reduction averaged across subjects (e.g., Houghton et al., 2017; Specht et al., 2013). The few studies that have examined individual-level data suggest that there are likely inter-individual differences in the moment-to-moment association of urges and tics during FTT and TSUP (Brandt et al., 2016; Langelage et al., 2022; Schubert et al., 2021).

Between-subject differences in the processes maintaining tics could explain the large between-subjects variation in treatment response reported in the CBIT randomized controlled trials (Piacentini et al., 2010; Wilhelm et al., 2012) within-subject change patterns across treatment. Although studies examining moment-by-moment change highlight the importance of within-subject methodologies, they were not designed to directly test negative reinforcement patterns and within-session habituation in the context of HRT, primarily because participants rated their premonitory urges and tic intensity combined for all tics rather than for single urge-driven tics. To date, no studies have explicitly examined within-session habituation during HRT even though it is considered an important aspect of treatment. For example, based on the prevailing habituation-based behavioral model, the standard HRT protocol instructs patients to use CRs to suppress their tics each time they identify an urge to tic and to maintain the CR until the urge to tic subsides (Woods et al., 2008).

The current study drew upon dynamical systems theory and its accompanying analytic framework (Guastello & Gregson, 2016) to better understand how urges and tics change during TSUP and a single HRT session, and whether these patterns were consistent with automatic negative reinforcement and within-session habituation hypotheses. Dynamical systems theory accounts for, and can quantify, how change in any one measured variable is related to the change in a variety of other factors within a system by focusing on the stability of change patterns over time. Specifically, a dynamical systems framework envisions the urge-tic relationship as a cyclical, push-pull pattern where various behavioral and environmental factors (e.g., suppression attempts) are constantly disrupting the natural patterns of the cycle across time. Homeostatically, if tics and urges consistently return to their natural patterns (overcoming disruptions), this suggests that the patterns have inherently consistent properties, known as "stability," in dynamical systems theory (Butner & Baucom, 2019). In the experimental tasks described herein, examining whether tic suppression is a precursor to changes in the pattern of tics and urges (and how strong the urge-tic relationship remains when it is introduced) has the potential to inform the hypothesized mechanism underlying HRT.

Specifically, we applied several dynamical systems parameters to test two of the primary tenets of the behavioral model of tics and the purported mechanism underlying HRT (see Table 1). First, analyzing urge-tic coupling (i.e., the degree to which change in tic occurrence precedes urge change and vice versa) provides a test of the automatic negative reinforcement hypothesis, and whether this pattern is disrupted during tic suppression. Second, examining whether the homeostatic level of the urge changes when tics are suppressed provides a test of whether premonitory urges decrease during suppression in a pattern consistent with within-session habituation. Third, examining the change in stability of premonitory urges across FTT and TSUP can be more broadly relevant in elucidating learning processes that occur during tic suppression. Behavioral theory suggests that the pattern of urge change observed for any individual with tics has been established through a learning history that includes associations with other variables in the system (e.g., stimulus-stimulus and stimulus-response associations), and without interruptions to these repetitive associations, over time, the system becomes increasingly stable (i.e., habitual). The notion that increased stability represents learning and adaptation over time has been shown experimentally in other literature (e.g., Kostrubiec et al., 2012) and its application has been discussed in the context of other habitual behaviors (Barrett, 2014). Thus, examining how destabilization and restabilization occurs has the potential to improve our understanding of the mechanism underlying HRT.

The current study focuses on examining dynamical systems parameters at the within-subject level, during suppression of a single, urge-driven tic to facilitate description and quantitative mapping of processes and patterns that may differ across individuals during study procedures that mirror the first session of HRT. From a dynamical systems perspective, each participant/system is unique, and thus examining within-subject patterns in tics and urges, rather than averaging across participants, has the potential to provide important insights regarding individualized urge-tic patterns

Table 1
Summary of Terms

Aim	Behavior Theory Research Question	Dynamical Systems Term	Coding/centering	Term	Definition
1	Are tics and urges linked via negative reinforcement?	Coupling	FTT = 0 TSUP = 1	β_2 (Model 1)	Degree to which urge level predicts tic occurrence in subsequent second
				β_8 (Model 2)	Degree to which tic occurrence predicts change in urge in subsequent second
1	Is the negative reinforcement cycle disrupted during suppression tasks?	Uncoupling	FTT = 0 TSUP = 1	β_4 (Model 1)	Difference in degree to which urge level predicts tic occurrence in subsequent second between FTT and TSUP
				β_{10} (Model 2)	Difference in degree to which tic occurrence predicts change in urge in subsequent second
2	Does the urge reduce over the course of the suppression condition (habituation)?	Homeostatic level decrease	Urge centered at homeostatic level	β_{13} (Model 3)	Change in the homeostatic level over the course of the suppression condition
3	Does the urge pattern become disrupted (learning pattern broken) during the suppression condition?	Change in stability	FTT = 0 TSUP = 1	β_9 (Model 2)	Whether the urge is de-stabilized by suppression (compared to free to tic)
3	Does a new learned pattern become stronger over the course of the suppression condition?	Increased stability	Time X stability interaction	β_{15} (Model 3)	Whether the urge becomes more stable over the course of suppression, following destabilization of old pattern

and inform person-specific interventions (Molenaar & Campbell, 2009). Focus on within-subject change is also consistent with the behavior analytic single subject designs (Kazdin, 2021) and precision medicine approaches to identifying individual differences in psychopathology (e.g., Wolfers et al., 2020). Within-subject analyses examining purported treatment mechanisms are an important next step in understanding "what works for whom."

The overall aim of the current study was to develop and employ a novel method for analyzing urges and tics comprehensively within-subject during a lab-based HRT task. Specific aims were to (1) examine coupling of urges and tics to test the automatic negative reinforcement hypothesis, (2) examine whether urge levels decrease across tic suppression conditions consistent with within-session habituation, and (3) examine changes in urge stability to test broader systems-level change and disruptions of established reinforcement patterns.

Method

PARTICIPANTS

Participants were recruited through referrals to a university-based tic disorder specialty clinic, fliers, social media postings, and outreach to local Tourette Syndrome support groups. The full sample included 12 adults, ranging in age from 17–60 years (mean age 31 years), with a DSM-5 diagnosis of a PTD (either Tourette disorder, persistent motor tic disorder, or persistent vocal tic disorder [APA, 2013]). One participant did not fully complete study procedures, so their data were excluded. Participant demographic information is summarized in Table 2. Participants were included if they had at least one target tic that occurred at least once per minute during direct observation and reported that the target tic (described in Table 3) was preceded by a premonitory urge of at least moderate intensity (at least 4 on a 1- to 10-point scale). Participants were excluded if they (a) had tics that interfered with study procedures (e.g., manipulating a joystick), (b) had a self-reported history of a non-tic neurodevelopmental disorder, traumatic brain injury, seizure disorder, hydrocephalus, or neurologic conditions known to affect cognitive functions, or (c) had previously received three or more sessions of behavior therapy for a PTD during which tic suppression skills were taught.

PROCEDURES

Study procedures were reviewed and approved by the site's institutional review board. The full procedures took approximately 3 hours and included

Table 2
Demographic and Clinical Characteristics

Mean Age	31.2 years
Gender (# female)	5 (46%)
Ethnicity (# White)	10 (91%)
Tic Medication Status (# yes)	2 (18%)
Comorbidity (any)	8 (73%)
Attention-Deficit Hyperactivity Disorder	4 (36%)
Obsessive-Compulsive Disorder	2 (18%)
Mood disorder	6 (55%)
Anxiety Disorder	6 (55%)
YGTSS mean motor tic score	12.18/25
YGTSS mean vocal tic score	8.82/25
YGTSS mean total tic score	21.00/50
YGTSS mean impairment score	16.63/50
Mean Premonitory Urge for Tics Scale score	27.45/40

Note. YGTSS = Yale Global Tic Severity Scale.

informed consent, a diagnostic assessment to confirm a diagnosis of a PTD based on DSM-5 criteria (APA, 2013), and a series of experimental tasks. Although not reported in the current study, EEG data were collected from participants during the experimental tasks. EEG set-up took approximately 45–60 minutes, and participants remained fitted with the cap throughout the experiment.

Diagnostic Assessment

A telephone screen was first conducted with each participant to determine likely study eligibility. Following the telephone screen, participants were invited to the lab for an in-person visit. At this visit, they completed the informed consent process and the diagnostic assessment. The diagnostic assessment consisted of the Yale Global Tic Severity Scale (YGTSS; Leckman et al., 1989), a semistructured clinician-rated interview to determine tic severity. The YGTSS has good reliability and validity in determining tic severity in PTDs (Leckman et al., 1989; Storch et al., 2005). Participants also completed the Premonitory Urge for Tics Scale (PUTS; Woods et al., 2005), a self-report measure with good reliability and validity for assessing general premonitory urge severity, and a demographic form that included medication status and history of diagnosis of comorbid conditions.

Experimental Setup

Consistent with procedures validated by Brandt et al. (2016), participants were seated on a chair in front of a computer monitor that displayed a 10-point scale on the y-axis of a coordinated system presented on the right side of the screen. Participants manipulated an analog stick (joystick-like knob) on a video-game controller to indicate their urge on the computerized Likert scale, where "0" indicated no urge and "10" indicated the strongest possible urge that can be tolerated before ticcing. The rate of sampling was 1 Hz. Participants were able to see their current urge rating as well as a continuous history of their urge ratings in the previous 10 seconds, represented by a continuously updating horizontal line that crossed the screen to the left. The experimenter and a research assistant were in the same room as the participant for the duration of the experiment but largely separated from the participant by a screen divider. The research assistant was positioned such that they could observe tics and record them in real time using a keyboard. All conditions were videotaped to facilitate later coding of tics.

Preparation for Experimental Conditions

Prior to beginning the experiment, a target tic was chosen for each participant that (a) occurred at least once per minute based on direct, in-lab, observation, (b) was observable to the experi-

Table 3
Target Tics

		Tic per minute			% Change	
Participant	Target Tic	FTT	TSUP	HRTSUP	FTT to TSUP	FTT to HRTSUP
1	Align eyelid with line of vision	12.90	0.00	0.83	−100	−94
3	Hard eye blink	4.80	1.73	0.17	−64	−97
4	Huffing through nose	1.20	0.07	0.03	−94	−97
5	Neck stretch	3.00	0.63	0.00	−79	−100
6	Sniffing	10.10	1.33	0.00	−87	−100
7	Shoulder lift	2.10	0.33	0.67	−84	−68
8	Face scrunch	6.50	3.47	0.43	−47	−93
9	Nose scrunch	21.90	4.37	5.60	−80	−74
10	Hard eye blink	5.80	3.23	0.57	−44	−90
11	Snort	3.30	0.07	0.00	−98	−100
12	Head jerk	1.10	0.20	0.00	−82	−100

Note. FTT = Free to tic condition, TSUP = tic suppression condition, HRTSUP = habit reversal condition.

menters for coding, and (c) had an associated urge that was rated at least a 4/10 on a 10-point scale of urge intensity (where higher numbers indicated higher urge ratings). Before beginning the experimental tasks, participants practiced manipulating the analog stick to adjust their urges in the computer program for one minute. Participants then engaged in the experimental conditions, during which they rated their urge, and their tics were observed and recorded by the research assistant. At the start of each condition, participants were instructed to press a button on the controller to start the task and the urge recording, at which point the urge rating was pre-set to the midway point (rating of 5) on the 0–10 Likert scale. If at any point participants removed their hand from the controller, the recorded urge level remained at the last place to which the participant had moved it. Instructions were given at the beginning of each condition and participants were asked to repeat them as given. Reminders of the instructions were given every 10 minutes. At the end of each condition, participants were asked a series of questions to determine whether the manipulation was successful and if they had remembered the instructions (e.g., “Were you suppressing your tics?” and “What were the instructions for this trial?”). All participants demonstrated that they remembered and understood each task and all participants passed the manipulation check for all conditions.

Experimental Conditions

Conditions included free-to-tic (FTT), tic suppression (TSUP), and habit reversal tic suppression (HRTSUP; e.g., tic suppression using a CR). All participants engaged in the conditions/activities in the same order (FTT → TSUP → FTT → HRT procedures → HRTSUP → FTT; see Figure 1). This ordering was chosen so that the therapeutic procedures taught during HRT did not contaminate the TSUP condition. For the *FTT conditions*, participants were instructed to tic as they usually would while continuously rating their urge for ten minutes. For the *TSUP condition*, participants were asked to suppress their tics, to the best of their ability, for 30 minutes but were not given specific instructions for how to do so.

Prior to the HRTSUP condition, participants were provided with a single session of HRT (identical to a first session of typical clinically administered HRT) where they were taught to suppress their target tic using a specific CR. HRT was administered by a trained therapist and was employed using standardized procedures (Woods et al., 2008). This consisted of awareness training (AT) and competing response training (CR training). The purpose of AT was to teach participants to become more aware of each discrete occurrence of their tic. The first step in AT was response description, where participants described discrete movements involved in the tic and sensations that preceded their tic (i.e., urges or “warning signs”). Participants then practiced “catching” their target tics (i.e., signaling tic occurrence with a physical response) until they could detect 80% of their targeted tic over a 5-minute period (all participants were able to reach 80% identification). Next, participants engaged in CR training; they were taught to engage in a behavior directly incompatible with the tic, thereby preventing the tic from occurring. Consistent with standard HRT protocol, participants were instructed to engage in the CR contingent upon tic warning signs (i.e., urges) and maintain the CR until the urge to tic completely diminished. Consistent with established HRT protocols, CR practice continued until participants could correctly implement the CR to interrupt 80% of targeted tic occurrences over a 5-minute period. Participants were then instructed to suppress their target tic using the CR for 30 minutes (HRTSUP condition).

Data Collection

Urge ratings made by participants and tic observations by the research assistant were sent to Presentation®, a stimulus delivery and experiment control program that recorded these variables in real time. Urge ratings were updated once per second, and tics were recorded when they occurred, with a specificity of .01 seconds. Urge data were extracted from the Presentation® program, and

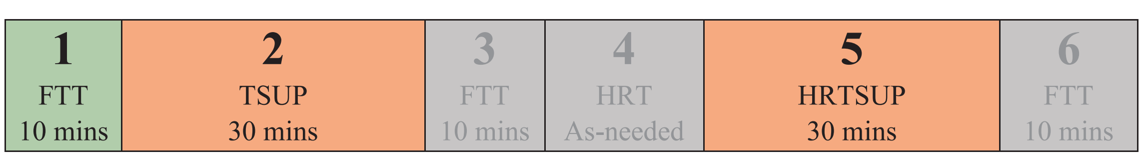

FIGURE 1 *Experimental Task Conditions. Note.* FTT = free-to-tic condition, TSUP = tic suppression condition, HRT = habit reversal procedures delivered consistently with in-clinic first HRT session, and HRTSUP = habit reversal condition. Conditions in grey were not used for current analyses.

tic occurrence was down-sampled to one data point per second. Data was then coded such that there were four variables for each participant: time in seconds (time zero was at initiation of the relevant experimental task), continuous urge intensity ratings along a scale of 0–10, binary presence of tic (0 or 1) during that second, and categorical condition (FTT, TSUP, HRTSUP). Each variable was represented each second for the entire 90-minute protocol, resulting in 600 cases for each of the 10-min FTT conditions, and 1,800 cases for each of the two 30-min suppression conditions (TSUP and HRTSUP). Categorical condition was coded differently depending on the conditions that were relevant for each separate analysis. All conditions were not included for all analyses (e.g., only FTT vs. TSUP and FTT vs. HRTSUP were used for comparisons of changes in urge coupling effects).

Reliability and Quality Assurance

To calculate interobserver agreement and procedural integrity, a second coder viewed randomly selected segments from each experimental condition for each participant and coded each observation for the presence/absence of the target tic. Specifically, the second observer re-coded 20% of each FTT, TSUP, and HRTSUP condition for each participant (one randomly selected segment for each 10-min FTT condition and three randomly selected segments for each 30-min TSUP and HRTSUP condition). To calculate agreement, partial-interval coding was used consistent with methods from Himle et al. (2006). Specifically, each coded section was divided into bins of 3 seconds (yielding 40 data points for each 2-min period). Each bin was then coded as an agreement (dummy code = 1) or disagreement (dummy code = 0) between the re-coded and originally coded data. Percent agreement was determined by dividing the number of bins indicating agreement by the total number of bins and multiplying by 100. Separate agreement estimates were calculated for each condition for each participant (yielding three estimates per participant). Percent agreement estimates averaged 96.8% (range: 82.5%–100%).

ANALYTIC PLAN

The goal of the analyses was to use within-subject, quantitative methods to map the complex change in urges and tics, and compare whether the patterns were different, within-subject, for each condition. Urge-tic coupling, homeostatic level of return (herein referred to as homeostatic level), and destabilization potential were modeled using autoregressive equations applied separately to each participant's time series data. The autoregressive equations were applied to time second-by-second series data by modeling the degree to which variables at one time point (t) predicted variance in the value of the variables at the following time point (t+1). Given that each condition was at least 10 minutes long, there were at least 600 data points per participant per condition, which is well beyond adequate power needed to detect even small effect sizes within-subject (Liu, 2017). To assess urge/tic coupling, change in destabilization potential, and homeostatic level across FTT and TSUP conditions, we used Equations (1) and (2), where condition was a binary variable containing only the FTT and TSUP conditions. To examine change in urge homeostatic level and destabilization potential across the TSUP condition, Equation (3) was utilized. All analyses conducted with the TSUP condition (FTT vs. TSUP comparisons and change across TSUP condition) were run in an identical fashion substituting HRTSUP for the TSUP condition. Statistically significant patterns found on the individual level will be summarized descriptively for the whole sample.

$$\mathrm{Logit(tic)}_{t+1} = \beta_0 + \beta_1 \mathrm{tic}_t + \beta_2 \mathrm{urge}_t + \beta_3 \mathrm{condition}_t + \beta_4 (\mathit{urge} \times \mathit{condition})_t + \beta_5 (\mathit{tic} \times \mathit{condition}) \tag{1}$$

$$\mathrm{urge}_{t+1} = \beta_6 + \beta_7 \mathrm{urge}_t + \beta_8 \mathrm{tic}_t + \beta_9 \mathrm{condition}_t + \beta_{10} (\mathit{tic} \times \mathit{condition})_t + \beta_{11} (\mathit{urge} \times \mathit{condition}) \tag{2}$$

$$\mathrm{urge}_{t+1} = \beta_{12} + \beta_{13} \mathrm{urge}_t + \beta_{14} \mathrm{time} + \beta_{15} (\mathrm{urge} \times \mathrm{time}) \tag{3}$$

Aim 1: Examine Coupling of Urges and Tics

Aims are outlined in Table 1. Coupling estimates (β_2 and β_8) from Models 1 and 2 represented the degree to which urge level predicted likelihood of tic occurrence in the subsequent second (urge level pre → tic), and the degree to which tic occurrence predicted subsequent changes in urge level (tic → urge level post), respectively. We hypothesized that the coupling estimates would be significant in FTT (with β_2 positive and β_8 negative), suggesting a pattern in which urges increase before, and decrease after, tic occurrence, which would be consistent with the negative reinforcement hypothesis. To examine whether the strength of the coupling between tics and urges changed between FTT and TSUP/HRTSUP, the coupling interaction estimates were examined (β_4 and β_{10}) and Cohen's *d* effect sizes (for unequal group sizes) were calculated. We hypothesized that the coupling interaction estimates would be negative for *urge level* *pre* → *tic*, which would indicate that the coupling effects were weakened in TSUP and HRTSUP, supporting the notion that the negative reinforcement pattern is disrupted by tic suppression.

Aim 2: Examine Urge Ratings Across TSUP and HRTSUP (Within-Session Habituation)

Model 3 was applied to urge ratings in the TSUP and HRTSUP conditions in order to examine changes in the urge level over time during tic suppression with and without the use of a CR. The homeostatic level for TSUP/HRTSUP was calculated and the urge data was transformed to be centered at the homeostatic level to aid the interpretation of the impact of time on homeostatic level. The time-effect estimate (β_{14}) represented the degree to which the urge homeostatic level changed each second during TSUP/HRTSUP (also linearly transformed to aid in interpretation). We predicted that this estimate would be significant and negative for both suppression conditions, which is what would be expected from the habituation model (i.e., within-session habituation).

Aim 3: Examine Changes in Urge Destabilization Potential

Estimates of the degree to which current urge rating predicts future urge rating ("own effect"; β_7) represented the destabilization potential (with low destabilization potential suggesting a stable system), in regard to urge patterns in FTT (when FTT = 0). Regarding destabilization potential, higher values suggest more potential for destabilization. Values between zero and one would suggest that destabilization potential is low (e.g., a stable system). Values greater than one would suggest that the potential for destabilization is high, such that when perturbed from the homeostatic level, the urge does not return (Butner & Baucom, 2019). We hypothesized that estimates for the FTT condition would be stable, learned systems, and demonstrate low destabilization potential (e.g., urge pattern (i.e., values < 1). Further, we examined estimates and associated effect sizes of the own effect × condition interaction (β_{11}), representing the degree to which the destabilization potential of the urge is different between FTT and TSUP/HRTSUP. We hypothesized that this interaction estimate would be significant and positive, indicating that destabilization potential was higher in TSUP compared to FTT (less stable) and that the urge pattern was disrupted by suppression. Finally, the own effect × time interaction estimate $(\beta_{15})_{in}$ Model 3 (applied just to the TSUP and HRTSUP conditions) represents the degree to which destabilization potential changed each second. A negative and significant estimate would indicate that destabilization potential decreased over time (increase in stability over time). If the urge pattern became more stable over the course of the TSUP and conditions, it would suggest that the urge is re-organizing following the disruption to the pattern.

Results

DATA MANAGEMENT

All statistical procedures and data management were conducted in R version 3.6.3 (R Core Team, 2016). For each participant, urge and tic data were inspected for implausible values through descriptive statistical analyses and visual review of graphs. Due to technical errors with Presentation®, there were infrequent occasions where one time variable (one specific second) was represented twice (i.e., information was recorded twice for one time point) and occasions where one time variable was missing. When a time variable was represented twice, the duplicate was deleted. This occurred for between 0–5 rows per condition for all participants except for one participant, for whom it occurred 41 times across three conditions (out of 42,000 seconds, or for .1%, due to high frequency of tics for this participant). When a row (representing a second) was missing, that row was added with the relevant second, and then the values for the other variables (e.g., urge rating, tic occurrence) were coded as missing. Less than .01% of data were missing for all participants, so listwise deletion was used. The number of tics in each relevant condition is summarized in Table 3.

MODEL APPROPRIATENESS

For each model estimated for each participant, we plotted the residuals across time. Each plot was analyzed visually to assess for random distribution (representing random error). All residual patterns appeared random, and thus no transformation of the data or changes to the model were deemed necessary.

AIM 1: EXAMINE COUPLING OF URGES AND TICS (NEGATIVE REINFORCEMENT)

Estimates and significance testing for coupling results are summarized in Table 4a. In the FTT condition, the *urge level pre* → *tic* coupling estimate (β_2) was statistically significant for 9 of 11 participants. For these 9 participants, higher urge ratings were associated with an increased likelihood of tic occurrence in the subsequent second. Additionally, during this condition, the *tic* → *urge level* estimates (β_8) were significant for 8 of 11 participants. However, for 7 of 8 of these participants, this relationship was the opposite of what

Table 4a
Aim 1: Coupling Estimates

Part.	Tic → Urges FTT (1 sec)	Urges → Tic FTT	Urge → Tic Δ (FTT vs. TSUP)	Urge → Tic Δ (FTT vs. HRTSUP)
1	0.686*	0.202*	–	−0.057
3	0.065	0.293*	−0.341*	−0.043
4	−0.488*	0.608*	1.085	14.780
5	0.199*	−0.162	0.786*	–
6	0.236*	0.234*	0.093	–
7	0.049	−11.319	11.147	11.695
8	0.884*	0.541*	0.220	0.413
9	0.390*	0.173*	0.056	0.109*
10	0.047	0.269*	−0.258*	−0.717*
11	0.280*	0.432*	0.147	–
12	0.661*	0.439*	−0.426*	–

Note. FTT = Free to tic condition, TSUP = tic suppression condition, HRTSUP = habit reversal condition. Missing values occurred when there were no instances of tics in one of the relevant conditions (TSUP or HRTSUP), and thus changes from FTT to that condition could not be analyzed.
* $p < .05$

was expected: tic occurrence predicted an increase in the urge in the subsequent second. Only 1 participant showed results in the expected direction for this relationship (i.e., that tic execution is followed by a subsequent decrease in the associated urge). Upon visual inspection of the data, it became clear that 1 second was not a sufficient amount of time to account for participant reaction time in recording their urge change (see Figure 2, participant 12), or account for decrease in urge following a burst of tics (see Figure 2, participant 1). As such, for participants who did not show the expected tic-urge reduction pattern (91% of the sample), we conducted post-hoc analyses to determine when, and if, urges decreased over a longer time interval following the tic. Results of these post-hoc analyses revealed that 3 participants demonstrated a decrease at a 4-second lag, 1 additional participant demonstrated a decrease at a 5-second lag, 1 at a 6-second lag, and 1 at a 9-second lag, for a total of 7/11 participants showing a decrease in urge following the tic (see Table 4b). The remaining 4 participants did not show a decrease at any lag under 10 seconds (see Figure 2, participant 5, for an example).

Considering both types of coupling estimates together, as well as the post-hoc analyses (*urge level* → *tic* and *tic* → *urge level*), 7 participants showed the predicted pattern in FTT in which urges increased prior to a tic and decreased following a tic, however for most of these participants, it took longer than 1 second following the tic for the urge to decrease. For 2 additional participants, higher urges increased the likelihood of a tic, but tic did not predict decrease in urge. For the remaining 2 participants, there was not a significant relationship for either coupling estimate.

The interaction estimates (β_4 and β_{11}) were also examined to determine whether the coupling relationships differed across the FTT and TSUP/HRTSUP conditions. One participant did not have tics in TSUP, so the interaction estimates for that participant could not be calculated. For 3 of the 10 participants, urges and tics uncoupled between the FTT and experimental conditions. Specifically, for these 3 participants, the *urge level* → *tic* relationship was weaker in TSUP compared to FTT, which is consistent with the hypothesis that suppression functions to uncouple urges and tics. For 1 participant, the *urge level* → *tic* relationship became stronger during suppression. Cohen's *d* effect sizes for these significant interactions were minimal to small (absolute values of effect sizes ranged between .06 and .15). For the remaining 6 participants, an uncoupling pattern did not emerge. The same analyses comparing FTT to HRTSUP yielded similar results. Although only 1 participant showed a pattern consistent with uncoupling (Table 4a, participant 10), 4 additional participants exhibited no tics in the HRTSUP condition, which is consistent with uncoupling; however, analyses could not be conducted due to lack of tics in that condition. One additional participant showed more coupling in HRTSUP (i.e., stronger *urge level* → *tic* relationship). For the remaining 5 participants, no changes in coupling between FTT and HRTSUP occurred.

Aim 2: Examine Urge Ratings Across TSUP and HRTSUP (Within-Session Habituation)

Table 5 summarizes how the homeostatic level of return changes across time for TSUP and HRTSUP. Homeostatic level change across time

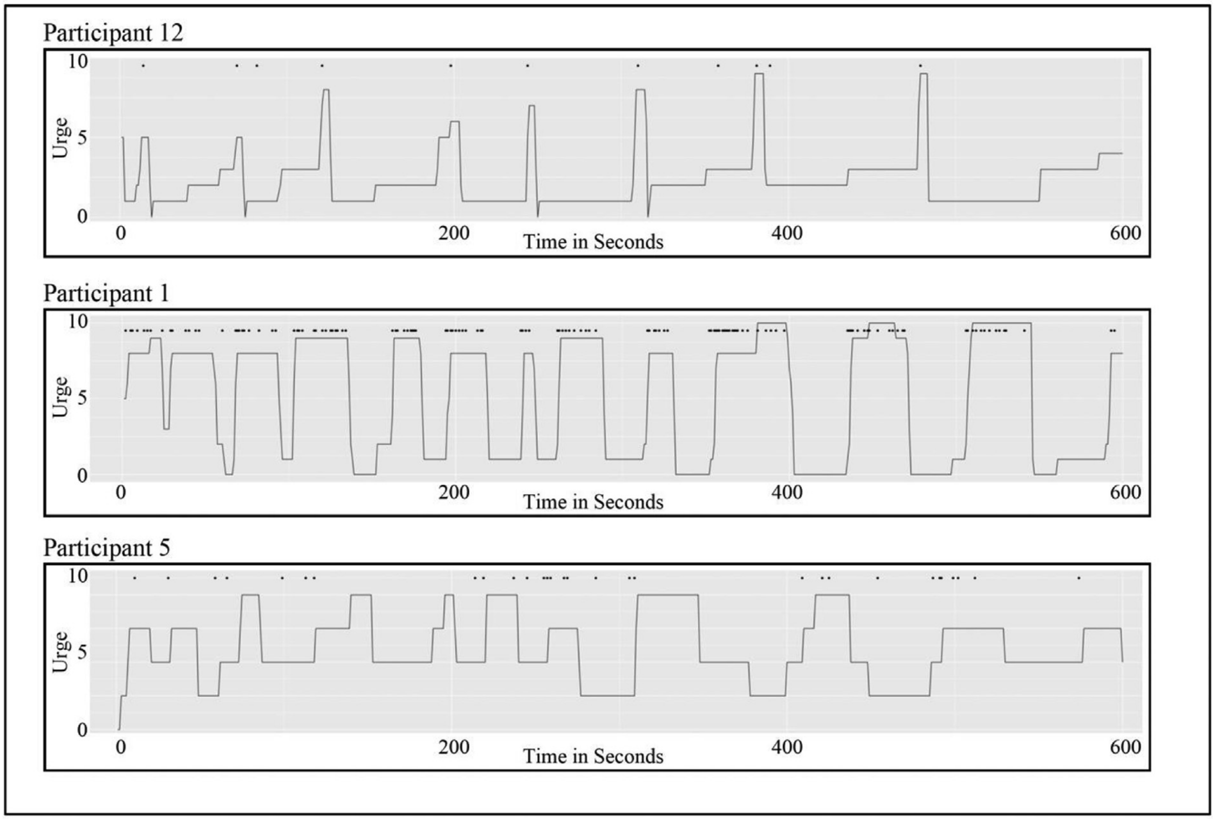

FIGURE 2 *Selected Time Series, Free-to-Tic Condition. Note.* Continuous urge rating represented by line, tic occurrence represented by dot.

(b_{14}) was analyzed to determine whether urge level significantly decreased during TSUP and HRTSUP. The homeostatic level decreased significantly over the course of the condition for two participants in TSUP (see participants 1 and 6 in Table 5). The setpoint decreased over the course of HRTSUP for three of 11 participants (Table 5, participants 4, 5, and 9). These results demonstrate that only 1 of the 11 participants showed a pattern that would be consistent with what would be expected if the individual habituated to urges during TSUP, and only 3 showed a pattern consistent with within-session habituation in HRTSUP. Despite generally having fewer tics during TSUP and HRTSUP, most participants reported a similar urge level over the course of these suppression tasks.

Table 4b
Aim 1: Post-hoc Coupling Estimates at Lag

Participant	Lag (seconds)	Tic → Urges FTT	*p*-value
1	4	−0.186	0.002
3	–	–	–
4	1	−.488	<0.001
5	–	–	–
6	9	−0.079	0.035
7	–	–	–
8	4	−0.364	<0.001
9	6	−0.237	<0.001
10	–	–	–
11	4	−0.390	<0.001
12	5	−2.408	<0.001

Note. FTT = Free to tic condition.

AIM 3: CHANGES IN URGE DESTABILIZATION POTENTIAL

Estimates for Aim 3 are summarized in Table 6. Destabilization potential estimates for all the participants during FTT were <1, suggesting a stable system (i.e., that the urge pattern was not easily destabilized). For 9 of the 11 participants, the urge destabilization potential was higher in TSUP compared to FTT (e.g., less stable), and effect sizes for these 9 participants ranged from small to large (Cohen's *d* ranged from .11 to 1.89). Similarly, when comparing FTT to HRTSUP, the urge destabilization potential was significantly higher in HRTSUP compared to FTT for 8 of 11 participants, with similar effect sizes. This suggests that, for most participants, the pattern of the urge was significantly disrupted (destabilized) during tic suppression. Finally, to examine whether destabilization potential decreased over the course of

Table 5
Aim 2: Change Set Point Level of Urge Level Over 30 Minutes

Participant	TSUP	HRTSUP
1	−0.061*	−0.020
3	−0.013	−0.002
4	−0.008	−0.280*
5	0.003	−0.051
6	−0.059*	0.033
7	0.013	−0.010
8	0.038	−0.012
9	0.013	−0.172*
10	0.061	−0.040
11	−0.037	0.002
12	0.002	−0.021

Note. TSUP = tic suppression condition, HRTSUP = habit reversal condition.

the TSUP and HRTSUP conditions (i.e., pattern increasingly stabilized), we used the estimate for interaction *own effect* × *time* from Model 3 (b_{15}). Destabilization potential did not appear to decrease for any participants over the course of TSUP or HRTSUP, and in fact for 3 participants during TSUP and 1 additional participant during HRTSUP, the destabilization potential increased, indicating that the urge pattern continued to destabilize over the course of the condition. For the remaining 9 participants in TSUP and 10 participants in HRTSUP, there was no change in destabilization potential, suggesting that the urge pattern had not yet begun to restabilize after a single session of TSUP or HRT.

Discussion

The current study applied a dynamical systems framework to tic and urge processes during an initial session of HRT to examine the hypotheses that (a) tics are maintained through automatic negative reinforcement, and (b) that the automatic negative reinforcement cycle is disrupted during tic suppression, resulting in a process of within-session urge habituation. Consistent with previous research regarding the negative reinforcement hypothesis (Specht et al., 2014), 9 of the 11 participants in this study demonstrated a pattern in which higher urge ratings were associated with increased likelihood of a subsequent tic during free-to-tic (FTT) conditions. Our findings also showed that approximately half of the participants demonstrated a pattern in which tic execution predicted a subsequent decrease in the associated urge.

There was considerable heterogeneity, however, in the temporal course during which the urge decreased following the execution of a tic, highlighting the methodological importance of decision making regarding fixed parameters used for analyses. For some of the participants, a decrease in the urge was not observed until after multiple tics had occurred (i.e., tic bouts). Similar bouting patterns have been reported in previous research (Brandt et al., 2016; Peterson & Leckman, 1998). Although retrospective self-report studies have suggested that individual tics result in urge reduction, it could well be the case that, for at least some individuals, a bout of tics represents a functional unit of tics. Although not examined in the current study, it may be that inter-individual differences result in part from developmental differences. There is a known increase in premonitory urge as individuals age (Banaschewski et al., 2003), which has been tied to the urge-tic cycle in a recent study by Langelage and colleagues (2022). Collectively, some of our participants showed patterns consistent with the negative rein-

Table 6
Aim 3: Stability Estimates

Participant	FTT	TSUP	FTT vs. TSUP Change	HRTSUP	FTT vs. HRTSUP Change	Change over 30 mins	
						TSUP	HRTSUP
1	0.940	0.990	0.051*	0.944	0.004	0.000203	0.000053
3	0.955	0.979	0.024	0.989	0.034*	0.000294	−0.000078
4	0.917	0.960	0.043*	0.924	0.007	0.000318*	0.001310*
5	0.947	0.961	0.013	0.973	0.026*	0.000338*	0.000227
6	0.937	0.985	0.048*	0.950	0.013	0.000228	0.000782
7	0.037	0.962	0.925*	0.977	0.940*	0.000446*	0.000301
8	0.850	0.958	0.108*	0.978	0.128*	0.000350	−0.000158
9	0.916	0.960	0.044*	0.962	0.046*	0.000411	−0.000482
10	0.911	0.974	0.063*	0.965	0.054*	0.000321	−0.000670
11	0.877	0.979	0.102*	0.966	0.089*	0.000266	−0.000108
12	0.881	0.995	0.113*	0.982	0.101*	0.000131	−0.000244

Note. FTT = Free to tic condition, TSUP = tic suppression condition, HRTSUP = habit reversal condition.
* $p < .05$

forcement hypothesis, but this process occurred quite heterogeneously across individuals and tics.

Another primary tenet of the urge-tic relationship in the behavioral model is that tic suppression disrupts the urge-tic cycle, and prolonged exposure to premonitory urges results in within-session habituation (Verdellen et al., 2008). Our procedures modeled the first session of HRT focused on facilitating within-session habituation, and our results were, for the most part, inconsistent with what would be expected during this session based upon the habituation hypothesis. Uncoupling of the tic and urge only occurred for 4 of 11 participants during tic suppression. Similarly, we found that urge level did not decrease over the course of the tic suppression condition for any participant. These within-subject findings are consistent with results from at least one other study (Specht et al., 2013) that failed to find urge reduction over the course of a 40-min tic suppression task. Although our sample is not large enough to be representative of the population of individuals with tics, the fact that none of our participants experienced within-session urge habituation adds support to recent calls for the examination of alternative mechanistic processes underlying HRT (Essoe et al., 2021; Langelage et al., 2022). Additionally, although we did not formally compare TSUP and HRT in the current study, our findings suggest that, overall, patterns of urge change over time were similar in the two conditions, providing initial evidence that suppression with and without use of a CR may be similar in this context.

Our lack of findings regarding urge-tic uncoupling and subsequent within-session habituation, especially in the context of inconsistency in the extant literature, opens the possibility of other mechanistic explanations for tic symptom reduction through suppression-focused interventions, such as the role of inhibitory processes. Essoe et al. (2021) suggested that repeated attempts at tic suppression might result in tic reduction through increased cognitive control (e.g., inhibitory control). Petruo et al. (2019) compared participants with PTDs to healthy controls using a go/no go task and found evidence that inhibitory deficits in PTDs may be related to differences in perception-action binding (e.g., behaviors are more strongly connected to sensory stimuli, making them more difficult to inhibit). It is possible that tic suppression effectively decreases the strength of the existing perception-action binding and facilitates improved inhibitory control. Improving the ability to inhibit responses is also consistent with the notion of urge tolerance, where individuals increase tolerance to the urge over time and while specific urge levels do not change, distressing consequences of high urges (e.g., tics, discomfort) still diminish because the individual has learned to inhibit these responses with practice.

A dynamical systems framework also may offer some insight into the mechanism underlying HRT. When we compared stability between FTT and TSUP, we found that for the majority of participants, the urge pattern became significantly less stable during TSUP. From both a dynamical systems and behavioral perspective, such a disruption is necessary for new patterns of responding to develop (e.g., through intervention; Barrett, 2014). Thus, suppression appears to be an important aspect of the intervention in that it facilitates change, despite that the change is not consistent with interruption of automatic negative reinforcement or habituation in the short term. Although quite speculative, it could be that the destabilization that occurs during tic suppression could be unpleasant (i.e., punishing) for the individual suppressing their tics (e.g., urges and other variables in the system fluctuate more and are unpredictable). Upon repeated engagement in suppression, it could be that the system begins to stabilize more and more quickly, reducing the punishing consequences of suppressing.

Beyond theoretical implications, the current study has several implications for intervention. Understanding individual differences in urge and tic changes during suppression can begin to explain the wide range of individual differences in response to interventions. For example, our results demonstrated that there may be differences in the degree to which urges subside upon tic expression or suppression, which would affect the automatic negative reinforcement process. It could be that individual differences in the processes that occur over the course of HRT are related to the large differences in improvement in tic symptoms following intervention. For example, it could be that those individuals for whom tics and urges are uncoupled during suppression are more likely to respond to CBIT. The current results can inform psychoeducation given to patients during CBIT. For example, it may be helpful to discuss bouts of tics as a functional unit and apply the CR accordingly.

The findings from the current study should be interpreted within the context of several methodological limitations. First, the study enrolled a relatively small number of individuals and all analyses examined only within-subject effects; therefore, care must be taken in generalizing results broadly. Future studies using similar methodology would benefit from the inclusion of larger samples to allow for the testing of between-subject effects, such as coupling and uncoupling as a predictor of future urge change. Second, our suppression task was 30 minutes and procedures and results were consistent with those from Specht et al. (2013), but in contrast to the methods used by Verdellen et al. (2008), who reported findings consistent with within-session habituation when utilizing 2-hour suppression sessions. Future research examining the contexts that facilitate urge habituation will be necessary to understand these discrepant results (e.g., length of session, clinic versus lab, expectations regarding urge reduction). However, it is important to note that in other disorders where habituation has been more clearly linked to symptom improvement (e.g., OCD), within-session habituation is observed well within the limits of 30-minute sessions, and often much more quickly (e.g., Benito et al., 2018). One final limitation is that our suppression task involved only a single time point. Although this can inform mechanistic processes that occur during an initial session of HRT, future research should use similar autoregressive modeling with multilevel methods to examine how urge and tic patterns change both within/between sessions and within/between subjects over a full course of HRT. This would facilitate examination of several constructs relevant to HRT processes. Specifically, it could elucidate whether between-session habituation occurs or begins to occur after multiple sessions of HRT, and whether other urge-tic uncoupling and within-session urge patterns change with practice and/or over a full course of HRT.

In summary, the current study directly tested several assumptions of the behavioral model underlying the maintenance and treatment of PTDs, using methodology that allowed for the detailed examination of within-subject, second-by-second change in urges and tics. We conclude that there is some evidence to suggest that the automatic negative reinforcement cycle between urges and tics is disrupted through tic suppression, although this does not happen similarly for all individuals, and does not occur at all for others. We did not find evidence of consistent decrease in the premonitory urge over the course of a period of sustained tic suppression. However, results do show that the stable urge pattern that is present during free-to-tic conditions is disrupted during suppression of tics, suggesting that tic suppression changes the overall dynamics of tics and urges, and is a process that might be necessary for clinically relevant change.

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