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Speeded processing of grammar and tool knowledge in Tourette's syndrome

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Abstract

Tourette's syndrome (TS) is a developmental disorder characterized by motor and verbal tics. The tics, which are fast and involuntary, result from frontal/basal-ganglia abnormalities that lead to unsuppressed behaviors. Language has not been carefully examined in TS. We tested the processing of two basic aspects of language: idiosyncratic and rule-governed linguistic knowledge. Evidence suggests that idiosyncratic knowledge (e.g., in irregular past tense formation; *bring–brought*) is stored in a mental lexicon that depends on the temporal-lobe-based declarative memory system that also underlies conceptual knowledge. In contrast, evidence suggests that rule-governed combination (e.g., in regular past tenses; *walk* + *-ed*) takes place in a mental grammar that relies on the frontal/basal-ganglia-based procedural memory system, which also underlies motor skills such as how to use a hammer. We found that TS children were significantly faster than typically developing control children in producing rule-governed past tenses (*slip–slipped*, *plim–plimmed*, *bring–bringed*) but not irregular and other unpredictable past tenses (*bring–brought*, *splim–splam*). They were also faster than controls in naming pictures of manipulated (*hammer*) but not non-manipulated (*elephant*) items. These data were not explained by a wide range of potentially confounding subject- and item-level factors. The results suggest that the processing of procedurally based knowledge, both of grammar and of manipulated objects, is particularly speeded in TS. The frontal/basal-ganglia abnormalities may thus lead not only to tics, but also to a wider range of rapid behaviors, including the cognitive processing of rule-governed forms in language and other types of procedural knowledge.

Keywords: Procedural memory; Morphology; Basal ganglia; Picture naming; Past tense; Regular inflection

Tourette's syndrome (TS) is a developmental disorder characterized by the presence of verbal and motor tics (APA, 1994). Tics, which may be expressed as "simple" or "complex" motor movements or vocalizations (e.g., "simple" grunting, or "complex" shouting of phrases), are both fast and involuntary (see references below and Tulen, Groeneveld, Romers, De Vries, & Van De Wetering, 2001). The tics appear to be caused by disturbances of the basal ganglia and closely connected regions of cortex, especially motor and cognitive regions of the frontal lobes (Albin & Mink, 2006; Albin, Young, & Penney, 1989; Bradshaw, 2001; Singer & Wendlandt, 2001). Such disturbances are reflected in structural abnormalities of the basal ganglia and frontal cortex (Fredericksen et al., 2002; Kates et al., 2002; Ludolph et al., 2006) and in abnormal levels of dopamine, a crucial neurotransmitter crucial in frontal/basal-ganglia circuits (for review and discussion, see Albin, 2006; Kienast & Heinz, 2006; Mink, 2006; Rauch & Savage, 1997; Singer & Wendlandt, 2001). The frontal/basal-ganglia abnormalities are thought to result in decreased inhibition of frontal activity, leading to a hyperkinetic behavioral profile and an inability to suppress tics (Albin & Mink, 2006; Osmon & Smerz, 2005).

Language in Tourette's syndrome has not been thoroughly examined. Whereas much attention has been focused on vocal tics (Frank, 1978; Gates et al., 2004; Goldenburg, Brown, & Weiner, 1994; Lang, Consky, & Sandor, 1993; Martindale, 1976; Peterson et al., 1998; Serra-Mestres, Robertson, & Shetty, 1998; Singer, 1997; Van Borsel & Vanryckeghem, 2000; Woods, Watson, Wolfe, Twohig, & Friman, 2001), few studies have

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investigated non-tic-related language. Moreover, these few studies have relied on standard neuropsychological measures and clinical impressions (Brookshire, Butler, Ewing-Cobbs, & Fletcher, 1994; Legg, Penn, Temlett, & Sonnenberg, 2005; Ludlow, Polinsky, Caine, Bassich, & Ebert, 1982; O'Quinn & Thompson, 1980; Scheurholz, Baumgardner, Singer, Reiss, & Denckla, 1996). While they have reported some abnormalities, particularly in expressive language, a comprehensive profile of language in the disorder is still lacking (Legg et al., 2005).

Here we attempt to extend our understanding of the language profile in Tourette's syndrome by examining two basic aspects of language: idiosyncratic and rule-governed knowledge. Idiosyncratic knowledge includes all arbitrary sound-meaning associations (e.g., /kæt/refers to the small furry feline) and word-specific morphological and syntactic information (e.g., *spring* takes *sprang* as its irregular past tense form). Rule-governed knowledge, in contrast, underlies the combination of words and parts of words into complex words (e.g., in regular past tenses, such as *walk* + *-ed*), phrases and sentences (Pinker, 1999; Pinker & Ullman, 2002).

According to "dual-system" models (see Section 3 for single-mechanism models), all idiosyncratic linguistic knowledge, such as of sound-meaning associations and irregular morphophonology (e.g., *spring–sprang*), is stored in the mental lexicon (Pinker, 1999; Pinker & Ullman, 2002; Ullman, 2001a, 2001b). The lexicon depends on an associative memory that can generalize patterns from already stored forms to new ones (e.g., from s*ing–sang*, *spring–sprang*, *ring–rang* to the novel irregular past tense *spling–splang*). Thus, unlike a rote memory, this memory system is productive, though the extent of its productivity remains unclear. In contrast, rule-governed complex forms, such as real and novel regular past tenses, are generally computed by the mental grammar (e.g., *walk* + *-ed*, *blick* + *-ed*). This grammatical combination is a default process and applies to any form for which the associative memory system cannot produce an acceptable output. Thus failure to retrieve the memorized form *sprang* could result in the over-regularization error *springed*, while failure to associatively generalize *spling* to a novel form such as *splang* could result in the novel regularization *splinged*.

However, not all regular or other apparently rule-governed forms are predicted to be computed by the grammar (Hartshorne & Ullman, 2006; Pinker, 1999; Pinker & Ullman, 2002; Prado & Ullman, submitted for publication; Ullman, 2001a, in press-c). Of interest here, the past tenses of regular verbs whose stems are phonologically similar to those of irregular verbs (e.g., *glide–glided*) are predicted to be stored in memory rather than composed by the mental grammar; storage of these "inconsistent" regular past tense forms prevents their irregularization, e.g., *glide–glode* or *glide–glid*, cf. *ride–rod*e or *hide–hid* (Ullman, 1993, 2001a; Ullman, Maloof et al., submitted for publication). Thus both irregular and inconsistent regular inflected forms are expected to be stored in the lexicon, while "consistent" regulars, whose stems are *not* phonologically similar to the stems of irregulars (e.g., *walked*), are predicted to be generally composed by the mental grammar.

Evidence has linked the mental lexicon (including irregular inflected forms) and the mental grammar (including consistent regular inflected forms) to distinct neurocognitive systems, each of which is known to subserve non-language functions. Specifically, evidence suggests that lexical memory depends on the declarative memory system, whereas the mental grammar relies on the procedural memory system (Ullman, 2001b, 2004, 2005, 2006a, in press-c; Ullman et al., 1997).

These two memory systems have different characteristics and depend on largely distinct neurobiological substrates. Declarative memory subserves the learning, representation, and use of knowledge about facts and events, such as the fact that elephants live in Africa, or that you had pumpkin ravioli for dinner last night (Eichenbaum, 2001; Eichenbaum & Cohen, 2001; Mishkin, Malamut, & Bachevalier, 1984; Squire & Knowlton, 2000; Squire, Stark, & Clark, 2004). The system seems to be specialized for learning arbitrary pieces of information and the associations between them (Eichenbaum, 2001; Eichenbaum & Cohen, 2001; Poldrack & Rodriguez, 2003). The learned knowledge is at least partly (but not completely; Chun, 2000) explicit—that is, available to conscious awareness. The hippocampus and other medial temporal structures consolidate and retrieve new memories, which eventually come to depend largely on neocortical regions, particularly in the temporal lobes (Eichenbaum & Cohen, 2001; Hodges & Patterson, 1997; Martin, Ungerleider, & Haxby, 2000; Squire et al., 2004). Other brain structures also play a role in declarative memory, including Brodmann's areas (BA) 45/47 in inferior frontal cortex, which underlies the selection or retrieval of declarative memories (Ullman, 2006b). Declarative memory and hippocampal function can be enhanced by estrogen (McEwen, Alves, Bulloch, & Weiland, 1998; Resnick, Maki, Golski, Kraut, & Zonderman, 1998; Sherwin, 1988), perhaps via the modulation of acetylcholine (Packard, 1998) and/or BDNF (brain-derived neurotrophic factor) (Scharfman & MacLusky, 2005), both of which play important roles in declarative memory independent of estrogen (Egan et al., 2003; Freo, Pizzolato, Dam, Ori, & Battistin, 2002; Hariri et al., 2003; Pezawas et al., 2004).

The procedural memory system underlies the gradual implicit (non-conscious) learning of new, and control of long-established, motor and cognitive 'skills' and 'habits', especially those involving rules or sequences, such as riding a bicycle and using tools and other manipulated objects (Mishkin et al., 1984; Poldrack & Packard, 2003; Squire & Knowlton, 2000; Ullman, 2004; Willingham, 1998). This system, which is composed of a network of brain structures, is rooted in frontal/basal-ganglia circuits, in particular the caudate nucleus within the basal ganglia, and premotor regions and BA 44 within frontal cortex. It also encompasses other structures, including portions of superior temporal cortex and the cerebellum (Ullman, 2004). The neurotransmitter dopamine plays a particularly important role in procedural learning (Goerendt et al., 2003; Harrington, Haaland, Yeo, & Marder, 1990; Nakahara, Doya, & Hikosaka, 2001). Note that the term "procedural memory" is used here to refer *only* to one type of implicit, non-declarative, memory system (Squire & Zola, 1996), *not* to all such systems. Additionally, both the declarative and procedural memory systems refer here to the *entire* systems involved in the learning and use of the relevant knowledge or skills (Eichenbaum, 2000), not just to those structures or mechanisms underlying the learning of new knowledge or skills.

A wide range of evidence supports the view – known as the Declarative/Procedural model – that the mental lexicon depends on declarative memory, while the mental grammar involves procedural memory (Ullman, 2001b, 2004, 2005, 2006a, in press-b, in press-c; Ullman et al., 1997). Here we focus on evidence most relevant to present study.

Adult-onset patients with temporal neocortical damage, but relatively intact frontal/basal-ganglia procedural structures (e.g., in posterior aphasia, semantic dementia, or Alzheimer's disease) show relative sparing of motor and other procedural functions, but impairments in processing previously learned (i.e., established) semantic and lexical knowledge, including in the production of irregular and novel irregular past tense forms (e.g., *dig–dug*, *spling–splang*) (Cortese, Balota, Sergent-Marshall, Buckner, & Gold, 2006; Miozzo, 2003; Patterson, Lambon Ralph, Hodges, & McClelland, 2001; Tyler et al., 2002; Ullman, in press-a; Ullman et al., 1997, 2005) (but see Tyler, 2004). In contrast, adult-onset patients with frontal and/or basal-ganglia lesions, but relative sparing of temporal lobe structures (e.g., in anterior aphasia, non-demented Parkinson's disease, and Huntington's disease), often show impairments with motor skills, knowledge of tool use, naming tools and other manipulated objects, syntactic processing, and the production of consistent and novel regulars (e.g., *slip–slipped*, *splim–splimmed*) (Alexander, 1997; Grossman et al., 2000; Longworth, Keenan, Barker, Marslen-Wilson, & Tyler, 2005; Murray, 2000; Ullman, 2004, in press-b; Ullman et al., 1997, 2005). Moreover, patients with Huntington's disease (whose particular basal ganglia degeneration results in unsuppressed or "hyper" behaviors, such as hyperkinesia) often add additional affixes (*walkeded*, *blickeded, broughted*), whereas patients with Parkinson's disease (whose basal ganglia degeneration results in suppressed or "hypo" behaviors, such as hypokinesia) do not make these errors (Ullman, in press-a; Ullman et al., 1997).

The neurocognitive basis of idiosyncratic and rule-governed knowledge and its relation to declarative and procedural memory have been less well studied in developmental disorders. Several lines of evidence suggest that Specific Language Impairment is associated with deficits of grammar and of non-linguistic functions that depend on the procedural memory system, as well as abnormalities of the neural substrates of this system, with a relative sparing of lexical and declarative memory (Ullman, 2004; Ullman & Pierpont, 2005). A similar argument has been made for autism and dyslexia, although lexical and particularly grammatical functions have been less well studied in these disorders (Bonin, Hartshorne, & Ullman, 2006; Ullman, 2004; Walenski, Tager-Flusberg, & Ullman, 2006). However, it is not yet clear whether dissociations between "hyper" and "hypo" basal ganglia-related language profiles can be found across developmental disorders. Additionally, it should be pointed out that whereas previous studies of adult-onset and developmental disorders have focused on accuracy and errors, response time data may be critical, particularly in "hyper" basal-ganglia disorders such as TS, in which behaviors such as tics are not just unsuppressed, but also fast.

The linguistic contrast between idiosyncratic and rule-governed forms has not previously been examined in TS. However, some predictions can be made about these aspects of language on the basis of evidence from studies of declarative and procedural memory in the disorder. This evidence suggests that aspects of procedural memory may be abnormal in TS, whereas declarative memory remains largely spared.

First, *learning* in procedural memory appears to be impaired, at least in some tasks. Learning implicit probabilistic rules in the weather prediction task, which depends at least in part on the caudate nucleus, is impaired (Keri, Szlobodnyik, Benedek, Janka, & Gadoros, 2002; Marsh et al., 2004). However, problems with procedural learning have not been found in rotary pursuit, mirror tracing, and serial reaction time tasks, all of which depend at least in part on procedural memory structures (Channon, Pratt, & Robertson, 2003; Marsh, Alexander, Packard, Zhu, & Peterson, 2005).

The status of processing previously learned (established) procedural knowledge in TS is less clear. Although we are not aware of any studies that have directly examined this issue, some studies have probed functions that may relate to the processing of established procedural knowledge. In one study, TS subjects showed faster and more force-efficient performance than controls in (some, though not all) goal-directed movements, with no group differences in movement accuracy (Georgiou, Bradshaw, Phillips, Cunnington, & Rogers, 1997). In another study, mental rotation, which depends on procedural memory brain structures (Ullman & Pierpont, 2005), was found to be impaired in males with TS (relative to male controls), but was actually enhanced (more correct responses in a 5 min period, thus reflecting a combination of accuracy and speed) in females with TS (relative to female controls) (Alexander & Peterson, 2004).

Declarative memory appears to remain largely normal in TS. A number of tasks have probed learning in declarative memory. First, whereas implicit procedural learning in the weather prediction task is impaired, the same TS subjects show normal explicit (declarative memory) learning of other information in this task (Keri et al., 2002; Marsh et al., 2004). Second, spared object location memory was found in the same subjects who showed impairments at mental rotation and at implicit learning in the weather prediction task (Alexander & Peterson, 2004; Marsh et al., 2004). Third, list learning of both verbal and non-verbal material appears to be normal in TS (Brookshire et al., 1994; Channon et al., 2003). Finally, studies have reported spared performance at delayed recall, and though deficits in delayed recall have also been observed, at least in some cases these have been attributed to factors other than declarative memory itself (Channon et al., 2003; Sutherland, Kolb, Schoel, Whishaw, & Davies, 1982).

We are aware of three studies that speak to the processing of established lexical or other declarative knowledge in Tourette's syndrome. In one, TS children were spared at picture naming (Scheurholz et al., 1996). In another, performance in a stem completion task was normal (Channon et al., 2003), suggesting that established lexical representations, and the priming of these representations, remains intact in TS. Finally, a third study found normal performance on the Wechsler Abbreviated Scale of Intelligence, which was used as an indirect measure of declarative memory function (Marsh et al., 2004).

Biological evidence also supports the view that declarative memory and its biological substrates remain largely normal in TS and do not play a role in the symptoms of the disorder. The cholinergic (acetylcholine-based) system appears to be essentially intact and functioning normally in TS (Singer & Wendlandt, 2001). Circulating estrogen levels in women with TS show the normal menstrual cycle pattern and do not correlate with tic severity or expression (Kompoliti, Goetz, Leurgans, Raman, & Comella, 2001). A study testing for abnormalities of the BDNF gene (specifically in the transmission of the Met66 allele of the Val66Met polymorphism) found normal patterns (Klaffke et al., 2006). Although one study (Ludolph et al., 2006) reported decreased grey matter volume of left hippocampal gyrus (the only structural imaging study examining this structure that we are aware of), the functional impact of this decrease was not examined, and so its consequences on language and memory remain unclear.

Thus previous evidence suggests frontal/basal-ganglia abnormalities, a mixed profile of procedural learning, and no clear evidence regarding the processing of established linguistic or non-linguistic procedural knowledge. Declarative memory, on the other hand, seems to be largely, though perhaps not completely, normal. On the basis of this pattern of evidence we expected that the processing of rule-governed forms might be abnormal, whereas the processing of idiosyncratic linguistic knowledge should be largely spared. Similarly, abnormalities might be found in the processing of established procedural knowledge of manipulated objects, but not in the processing of established conceptual declarative knowledge (e.g., of non-manipulated objects). Importantly, the expected nature of any abnormalities in the processing of established procedural knowledge was not clear *a priori*: any such abnormalities could in principle manifest themselves in a number of ways, including lower accuracy, slower response times, or even fast response times, analogous to the rapid nature of tics and the speed increases observed in goal-directed movements in TS (Georgiou et al., 1997).

In the current study we examined these issues with two tasks, in which we measured both accuracy and response times. First, subjects were given an elicited production task of past tense forms that are thought to be processed either by the grammatical/procedural system (-*ed*-affixed forms: consistent regular past tenses, novel regularizations, and over-regularization errors on real irregulars) or in lexical/declarative memory (irregular past tenses, inconsistent regulars, and novel irregularizations). Importantly, contrasting these two types of forms allows one to examine lexical and grammatical aspects of language while holding other factors constant (Pinker, 1999; Pinker & Ullman, 2002). Second, subjects were given a picture naming task to test the production of object names that are expected to either involve manipulated object knowledge (e.g., *hammer*) or not (e.g., *elephant*), thus probing motor skill and conceptual knowledge while holding language factors (naming) constant.

Table 1
Subject information

	Tourette's	Controls	*t*-test
n	8	8	–
Age in years	12.4 (3.4)	10.9 (0.8)	$t_s(7.9) = 1.22, p = 0.25$
Full scale IQ	106.6 (15.4)	118.4 (12.4)	$t(14) = 1.68, p = 0.11$
Verbal IQ	112 (13.2)	121.8 (13.8)	$t(14) = 1.44, p = 0.17$
Performance IQ	103.3 (14.8)	112.1 (13.4)	$t(14) = 1.26, p = 0.22$

Note: Means (and standard deviations). *T*-tests are two-sample, equal variance, except for the age comparison, where the Satterthwaite approximation (t_s) was used to estimate degrees of freedom due to unequal group variance.

1. Methods

1.1. Subjects

Eight subjects diagnosed with Tourette's syndrome (7 male, 1 female) participated in this study (Table 1). Diagnosis was based on criteria established by the Tourette Syndrome Study Group (1993). Attention Deficit-Hyperactivity Disorder (ADHD) and Obsessive-Compulsive Disorder (OCD) are very common in TS (APA, 1994; Erenberg, 2005; Klaffke et al., 2006), so subjects with these comorbidities were not excluded. One of the TS subjects was diagnosed with ADHD, and one with both ADHD and OCD. Five of the seven TS subjects were taking psychoactive medications at the time of testing: one was taking clonidine and risperdone; 1 clonidine, risperdone, and clonazepam; 1 clonidine and dextroamphetamine; 1 clonidine and atomoxepine, and 1 just methylphenidate. In addition, 8 typically developing control subjects (7 male, 1 female) were tested (Table 1). Control subjects were free of any developmental or psychiatric disorders, based on DICA-IV criteria (Reich, Welner, & Herjanic, 1997).

All subjects were right-handed native English speakers, aged 8–17, with full-scale IQ scores greater than 80 (range 85–135). Handedness was assessed with a modified version of the Edinburgh handedness questionnaire (Oldfield, 1971). IQ was assessed with the Wechsler Intelligence Scale for Children-III (WISC-III; Wechsler, 1991), except for the oldest subject (17 years old), who was tested on the Wechsler Adult Intelligence Scale-III (WAIS-III; Wechsler, 1997). All subjects and their parents provided informed written consent prior to participation. The Institutional Review Boards of Georgetown University and Johns Hopkins University School of Medicine provided approval for this study. Participants provided written consent (caregivers) and assent (children) before beginning testing, and received a copy of the consent form.

1.2. Design, materials, and procedure

1.2.1. Past tense production task

Subjects were asked to produce the past tenses of verbs presented in sentence contexts (Prado & Ullman, submitted for publication; Ullman, Maloof, et al., submitted for publication). Four types of verbs were presented: 32 consistent regulars (e.g., *slip–slipped*) matched to 32 irregulars (e.g., *bring–brought*); 16 inconsistent regulars (e.g., *squeeze–squeezed*); and 32 novel verbs (*plaw*, *splim*) (Table 2). The stems of the consistent regulars shared their rimes with the stems of few or no irregulars. The irregulars did not include any no-change verbs (e.g., *beat–beat*) or doublet verbs (e.g., *dive–dived/dove*). The 32 consistent regulars and 32 irregulars were matched groupwise *a priori* on stem (unmarked form) and past tense frequency ($ps > 0.45$). The stems of the 16 inconsistent regulars were phonologically similar to the stems of irregulars. The 32 novel verbs are primarily expected to elicit regularized responses (*plawed*, *splimmed*), although half of these verbs were phonologically similar to the stems of real irregular verbs (e.g., *scring*, *splim*; cf. *sing*, *swim*), increasing the likelihood that subjects produce at least some irregularized responses (*scrang*, *splam*) (Ullman, in press-a).

As in other studies with the same version of the past tense production task used here (Prado & Ullman, submitted for publication; Ullman, Maloof et al., submitted for publication), three problematic verbs were excluded from all analyses: *sink* is a doublet verb, with two possible irregular past tenses (*sank*, *sunk*); the past tense of *bind* is also a verb stem (*bound*); and *owe* is the only

Table 2
Verbs in the past tense production task

Consistent regular	Irregular	Inconsistent regular	Novel
call–called	*bind–bound	blind–blinded	blide (i)
clear–cleared	bleed–bled	clean–cleaned	chawl
cry–cried	break–broke	climb–climbed	chay
cure–cured	bring–brought	earn–earned	cheel (i)
die–died	catch–caught	fill–filled	cleep (i)
drown–drowned	creep–crept	glide–glided	cray
dry–dried	deal–dealt	glow–glowed	freep (i)
fail–failed	dig–dug	heap–heaped	fring (i)
fan–fanned	flee–fled	please–pleased	glip
glue–glued	fling–flung	scream–screamed	loy
hire–hired	freeze–froze	screen–screened	nop
*owe–owed	hide–hid	slow–slowed	plaw
pass–passed	hold–held	squeeze–squeezed	pleave (i)
plan–planned	keep–kept	swell–swelled	plip
play–played	lend–lent	wipe–wiped	ploon
pray–prayed	lose–lost	yell–yelled	prap
roll–rolled	seek–sought		prass
sail–sailed	sell–sold		proy
scrape–scraped	*sink–sunk/sank		screep (i)
sigh–sighed	sleep–slept		scring (i)
sign–signed	slide–slid		shrake (i)
slip–slipped	sling–slung		shraw
spy–spied	spend–spent		shreep (i)
stay–stayed	stick–stuck		splaw
step–stepped	sting–stung		splim (i)
stop–stopped	stride–strode		splink (i)
stray–strayed	string–strung		spreel (i)
sway–swayed	sweep–swept		strite (i)
tie–tied	swim–swam		treep (i)
try–tried	teach–taught		tring (i)
view–viewed	tell–told		wape
whip–whipped	weep–wept		zole

Note: Verb stems, together with correct responses for real verbs. Verbs marked with '*' were excluded from all analyses (see text). Novel verbs designed to be phonologically similar to existing irregular verbs are followed by '(i)'.

single-phoneme verb, and moreover shares its rime with many more irregular stems than any other verb selected as a consistent regular (*owe* rhymes with the stems of seven irregular verbs; all other consistent regulars in this study rhyme with between zero and three irregulars). The remaining 31 consistent regulars and 30 irregulars were still matched on stem and past tense frequency ($ps > 0.8$).

All 112 verbs were pseudo-randomly intermixed into a single presentation list, with the different verb types evenly distributed throughout the list. Verbs with similar-sounding stems (e.g., *think*, *splink*) were never in adjacent positions. Stimuli were presented on the screen of a Macintosh computer using an in-house software presentation program with high timing accuracy (Prado & Ullman, submitted for publication; Ullman, Maloof et al., submitted for publication). Each verb stem was visually presented both alone and in the context of a sentence, with a second sentence eliciting the past tense (e.g., *dig*. *Every day I dig a hole. Yesterday I ______ a hole*.). The verb stem and the two sentences were displayed at the same time on the computer screen, one below the other. Subjects were instructed to produce the missing form as quickly and accurately as possible. Other than the stimulus verb (e.g., *dig*) and the words following this verb (e.g., *a hole*), the sentences for the different verbs did not differ. All post-verbal sentence completions were composed of two words, none of which were inflected or of low frequency.

Presentation of the stimulus initiated a software timer, which was terminated by the subject's oral response (via a microphone connected to the computer). Presentation of the next stimulus was either initiated by the experimenter by pressing a button after the subject had responded at least once, or proceeded automatically after fifteen seconds. There was a 3 second Inter-Stimulus Interval (ISI) between items. The entire session was audio-recorded on minidisc. Subjects were given 10 practice items before the task began: 3 regulars, 3 irregulars, and 4 novel verbs.

Table 3
Object names in the picture naming task

Commonly manipulated	Not commonly manipulated
accordion; bow; chopsticks; comb; corkscrew; dart; drum; dustpan; eraser; faucet; fork; guitar; hammer; harp; iron; paintbrush; paperclip; pencil; pliers; saw; scissors; screwdriver; shovel; stapler; stethoscope; stopwatch; sword; telescope; toothbrush; umbrella; wallet; wrench	ant; bat; beaver; chameleon; cheetah; chipmunk; eagle; elephant; flamingo; giraffe; gorilla; hummingbird; kangaroo; koala; lion; monkey; octopus; owl; panda; peacock; penguin; raccoon; scorpion; seahorse; skunk; spider; squirrel; swan; tiger; toucan; wolf; zebra

In order to code each response accurately (i.e., as a correct response or as a particular type of error), responses were transcribed phonemically by two trained transcribers: the experimenter, who transcribed responses during testing, and an independent transcriber, who transcribed from the recording. The rare disagreements were resolved by a third trained transcriber. Correct responses to real verbs are shown in Table 2. All other responses were coded as one and only one of the following response-types.

For regular verbs (whether consistent or inconsistent regulars), errors were coded as follows. 'Irregularized' errors (*slip–slup*, *squeeze–squoze*) were defined as plausible attempts to form an irregular past tense, based on similarity to existing past tense transformations (e.g., *slip–slup* has the same vowel transformation as *dig–dug*; *squeeze–squoze* is like *freeze–froze*). 'Unmarked' errors were defined as exact repetitions of the stem given to the subject (*slip*, *squeeze*). 'Inflection' errors were *-ing*- or *-s* affixed forms of the verb given to the subject (*slipping*, *squeezes*). 'Multiple *-ed*' errors were defined as verb stems given to the subject with two or more additions of the *-ed* affix (*slippeded*, *squeezededed*). 'Double-marked' errors were defined as irregularized errors plus the appropriate allomorph of the *-ed* suffix (*slupped*, *squozed*). 'Other' errors consisted of responses with more than one of any other type of error (*slupping*); intrusions of other words (e.g., *slip–flipped*); responses with phonological errors (*squeeze–skeezed*); and incomplete responses (*slip–sli*...). Note that there were no errors with both irregularizations and multiple *-ed* affixes, for any verb type (*squeeze–squozeded*, *bring–brungeded*, *splim–splammeded*).

For irregular verbs, 'over-regularized' errors consisted of the given stem plus the appropriate allomorph of the *-ed* affix (*bringed*). 'Past participle' errors were irregular past participle forms of the given verbs (possible only for irregular verbs for which a distinct irregular past participle exists; e.g., *break–broke–broken*). 'Over-irregularized' errors were plausible but incorrect attempts to irregularize the verb (*brung*). 'Double-marked' errors were defined as −*ed*-suffixed correct irregular or over-irregularized forms (*broughted*, *brunged*). All other errors were defined as for regular verbs.

For novel verbs (*splim*), 'regularized' responses were expected (i.e., the "expected response"), and were defined as the given stem affixed with the appropriate *-ed* allomorph (*splimmed*). Irregularized responses (*splam*), and all other unexpected responses (e.g., *splimming*, *splammed*), were categorized as for regular verbs.

1.2.2. Picture Naming Task

In this task subjects named pictures of objects (Table 3). Sixty-four pictures were presented: 32 objects that are commonly manipulated or otherwise physically interacted with (including, but not limited to, tools; e.g., *umbrella*, *hammer*), and 32 animals that are not commonly manipulated or physically interacted with, e.g., *lion*, *seahorse*. The object names for the 32 manipulated objects and 32 non-manipulated animals (hereafter "non-manipulated objects") were matched groupwise *a priori* on word (singular noun) frequency and syllable length ($ps > 0.6$). An additional 32 items were included as filler items, and are not analyzed here.

To confirm our classification of objects as manipulated or non-manipulated, we obtained manipulability ratings of all 64 objects. Seven adults from the Georgetown University community were asked to rate the manipulability of the depicted objects ("How likely are you to manipulate or physically interact with the depicted object") on a seven point scale, with 1 being least likely, and 7 most likely. Consistent with our *a priori* classification, objects identified as manipulated had a significantly greater mean manipulability rating than those classified as non-manipulated (5.89, s.e. 0.13 versus 1.51, s.e. 0.11; $t(62) = 26.06$, $p < 0.0001$).

The 96 pictures (i.e., including the 32 filler items) were pseudo-randomly intermixed and presented in a single list, with the object types distributed evenly across the list. Stimuli were presented on the screen of a Macintosh computer using the same in-house presentation program described above. Subjects were asked to name the depicted object as quickly and accurately as possibly. Presentation parameters (e.g., 15 second maximum presentation time and 3 second ISI), response-time measurement, audio recording, and transcription procedures were the same as in the past tense production task. Prior to presentation of the test items, subjects were given four practice items. Responses were coded as correct only if they precisely matched the expected name of the object. Thus abbreviated responses (e.g., '*brella* for *umbrella*) or descriptions (*Chinese sticks* for *chopsticks*) were considered incorrect, as were responses that contained phonological errors. This strict approach was taken to ensure comparability of response times across subjects for each item.

1.2.3. Analysis

For both the past tense production and picture-naming tasks, first responses in each task were analyzed using multilevel (hierarchical) regression models, with crossed random effects of subject and item. Accuracy (correct/incorrect) and response time constituted the dependent measures. A logit-link function (for binary outcome data) was used for accuracy analyses. For response time analyses, incorrect first responses and response time errors were excluded. Response time (RT) errors were defined as RTs that reflected a noise other than the subject's response (monitored by the experimenter during testing); response times less than 300 ms (which are too fast to reasonably reflect a subject's response); and cases where no RT was recorded (i.e., subject did not respond or response was not loud enough to trigger the timer). Such errors constituted 4.3% of responses for past tense production, and 3.1% of responses for picture naming. Responses with false starts (where the subject began to respond, paused, then started again) were also excluded from response time analyses (there were only 4 such responses, all in past tense production). Due to technical problems, data from one TS subject was not recorded during the past tense production task, requiring the exclusion of that subject from all past tense analyses. No subjects or items were removed from the picture naming data set.

Two steps were taken in order to reduce the skewness of the distribution of response times in each task: RTs were natural-log transformed, and subsequently extreme outliers were removed on the basis of visual inspection of the normal probability plot. For past tense production this led to the exclusion of ln-transformed RTs less than 6.3 or greater than 9.2, or 1.4% of the data. For picture naming, ln-transformed RTs, less than 6.4 or greater than 8.75, or 2.4% of the data, were excluded.

For both tasks, the independent variables were subject group (TS versus control), and, where appropriate, item type (consistent regular vs irregular verb; manipulated vs non-manipulated object). Subject group (TS versus control) was the sole independent variable in analyses of inconsistent regulars, novel verbs, and past tense production errors. Because hierarchical logistic regression models may be inaccurate with very small sample sizes, *t*-statistics from hierarchical logistic regressions (i.e., on accuracy or error rates) are shown only for comparisons in which the response-type constituted at least 10% of responses in both subject groups. Response time analyses were performed only on these response types, ensuring a sufficient number of response times for analysis. *F*-statistics are reported for main effects and interactions, and *t*-statistics for planned comparisons of group and item-type differences. Significance of all comparisons involving these factors was assessed with $\alpha = 0.05$. All *p*-values are reported as two-tailed. In all analyses, degrees of freedom were computed using the Satterthwaite approximation.

1.2.3.1. Covariates. A number of potentially confounding subject- and item-level factors were considered for inclusion as covariates in the regression models. See below for discussion of the statistical criteria for their inclusion. Four subject level factors were considered for both tasks: age, full scale IQ, verbal IQ, and performance IQ.

Several item level factors were also considered for both tasks (see below for item level factors specific to past tense production). First, natural log transformed item order (i.e., order of occurrence within the presentation list) was examined to account for any variability attributable to item presentation order (e.g., due to practice effects within the task) (Prado & Ullman, submitted for publication).

We examined two binary variables that reflect the type of sound at the beginning of the correct or expected response, as this can affect computer-recorded response time measurements: one variable coding whether or not the initial phoneme of the response was a fricative, and another coding whether or not it was a plosive (Kessler, Treiman, & Mullennix, 2002; Prado & Ullman, submitted for publication).

Word frequency may influence the time to produce words in tasks such as past tense production and picture naming (Alegre & Gordon, 1999; Barry, Morrison, & Ellis, 1997; Oldfield & Wingfield, 1965; Prado & Ullman, submitted for publication; Stemberger & MacWhinney, 1986; Ullman, Maloof et al., submitted for publication). We considered both past tense and stem (unmarked form) frequency in past tense production, and the surface frequency of the correct response in picture naming. Frequency counts were calculated as the natural log of the sum of the raw frequencies–plus 1 to avoid ln(0)–of two English language counts: (1) the Francis and Kucera count (Francis & Kucera, 1982), derived from 1 million words of text drawn from a variety of sources (henceforth "FK"); and (2) a frequency count extracted by a stochastic part-of-speech analyzer from 44 million words of unedited Associated Press news wires from between February and December 1988 (henceforth "AP") (Church, 1988; Prado & Ullman, submitted for publication; Ullman, 1999; Ullman, Maloof et al., submitted for publication).

The phonological length of a spoken response is also likely to affect response time, as longer words may require more time for syllabification and articulatory planning (Levelt, Roelofs, & Meyer, 1999; Meyer, Roelofs, & Levelt, 2003). The phonological length of the correct or expected response in both tasks was thus considered. Past tense length was computed as the number of phonemes, since all irregular and consistent regular past tenses were monosyllabic (Prado & Ullman, submitted for publication; Ullman, Maloof et al., submitted for publication), and as the number of syllables for picture naming consistent with prior studies (Levelt et al., 1999; Meyer et al., 2003). In addition, verb-stem length (number of phonemes) was considered for the past tense production task, as the verb stem is likely to be held in working memory before production of the past tense form, and phonological length affects working memory performance (Baddeley & Hitch, 1974; Caplan, Rochon, & Waters, 1992).

Several additional item-specific covariates were considered solely for the past tense task. First, for real verbs only, we examined the imageability of the uninflected form of the verb (Bird, Howard, & Franklin, 2003; Bird, Lambon Ralph, Seidenberg, McClelland, & Patterson, 2003; Prado & Ullman, submitted for publication), using ratings from 1 (low imageability) to 5 (high imageability) (Prado & Ullman, submitted for publication). (Imageability ratings were not available for all items in picture naming, so imageability was not considered for that task.)

For both real and novel verbs, two phonological neighborhood measures were considered to account for the potential influence of phonologically similar verbs on the production of a past tense form. The "phonological neighborhood" of a past tense form is a function of the type and token frequency of phonologically similar and dissimilar verbs. For example, the production of *sang* from *sing* may be strengthened by similar stem-past pairings such as *spring–sprang*, but weakened by *bring–brought* and *wing–winged*. We considered two complementary neighborhood measures as covariates: 'same-class' and 'opposite-class' neighborhood strength (Prado & Ullman, submitted for publication).

'Same-class' neighborhood strength takes into account both "friends" and "enemies" in the *same* inflectional class (e.g., within irregulars). Same-class "friends" of a given *irregular* verb (e.g., *keep–kept*) are defined as those irregulars that share the same type of stem-past transformation, specifically, those that are in the same "family", following Pinker and Prince (1988). Same-class "enemies" of a given irregular are defined as those irregulars that share the same rime with either the given verb or any of its same-class friends, but have a different stem-past transformation, and are therefore not in the same family. Note that regular verbs do not have same class enemies, since all regulars have the same stem-past transformation. Same-class neighborhood strength was calculated by summing the frequencies (FK + AP) of same-class friends and subtracting the summed frequencies (FK + AP) of same-class enemies. If this frequency difference (D) was positive or zero, the same-class neighborhood strength was defined as $\ln(D + 1)$. If D was negative, it was defined as $-\ln(|D| + 1)$.

'Opposite-class' neighborhood strength can account for potential regular neighborhood effects on irregulars, and irregular neighborhood effects on regulars. Regular enemies of an irregular verb were defined as regular verbs with the same stem vowel as the irregular. Irregular enemies of a given regular verb were similarly defined as irregular verbs with the same stem vowel as the regular. Opposite-class neighborhood strength was calculated as the natural log of the summed frequencies (FK + AP) of the verb's opposite-class enemies, first adding 1 to avoid ln(0).

Two other phonological factors previously agued to be relevant to differences between regular and irregular verbs were also considered for all real and novel verbs. First, we constructed a variable to reflect whether or not the phonemes in the rime of the past tense form exhibit consistent voicing (e.g., the rime of the regular past tense *felled* is consistently voiced, as both /l/ and /d/ are voiced, whereas the rime of the irregular past tense *felt* is not, as /t/ is voiceless). This variable was examined because evidence suggests that two voiced phonemes within a coda may be less perceptually distinct, potentially accounting for differences in performance between regular (always consistently voiced) and irregular (not always consistently voiced) verbs (Bird, Lambon Ralph, et al., 2003). Second, we examined the number of phonological changes between the stem and past tense form (computed as in previous studies; Marcus et al., 1992; Ullman, Walenski, Prado, Ozawa, & Steinhauer, submitted for publication, since the past tenses of verbs with fewer stem-past changes may potentially be easier to produce.

Finally, we examined three variables that can capture certain order effects not accounted for by item order itself (Prado & Ullman, submitted for publication; Ullman, Maloof et al., submitted for publication): first, for real verbs, whether or not the previous verb presented to the subject was of the same inflectional class, i.e., regular or irregular, because repeating a similar response or producing a different type of response may affect response time and accuracy; second, for novel verbs, whether the previous verb was a regular verb (either consistent or inconsistent) or not (irregular or novel), as this may influence the inflectional pattern produced, especially for novel verbs; and third, for real as well as novel verbs, whether the previous verb was real or novel, because switching from a novel to a real item could also affect performance.

1.2.3.2. Covariate inclusion. Each of these subject- or item-level factors was included as a covariate in regression models only if it met certain specific conditions that suggested it might indeed confound the results. Therefore only a subset of the potential covariates was actually included in analyses, reducing the risk of overfitting the data. The following steps were taken to determine whether or not each factor would be included as a covariate.

First, it was determined whether each potential covariate was either *unbalanced* or *associated*. A factor was considered unbalanced if it differed between subject groups for subject level variables (Table 1), or between contrasted item types for item level variables (consistent regular versus irregular verbs for past tense production, and manipulated versus non-manipulated objects in picture naming). Whether or not a factor was unbalanced was determined by *t*-tests (for continuous variables; e.g., age, IQ, stem frequency), or Fisher's exact tests (for categorical variables; e.g., whether a word began with a fricative), using $p \leq 0.15$ as a significance threshold. This liberal significance threshold was chosen to avoid excluding (and thus not controlling for) covariates that might actually be confounding the data. In addition, a factor was considered unbalanced if the variance between the groups or item-types was highly unequal.

Association was tested by constructing a fixed-effects regression model that contained only the potential covariate as an independent variable, and mean subject scores (for subject-level covariates) or item scores (for item-level covariates) as the dependent variable. Mean accuracy was computed as a percentage score and mean RT as the mean ln-transformed response time. A covariate was considered to be associated if it predicted performance, again with $p \leq 0.15$ as a significance threshold. For past tense production, covariate association was examined separately for real verbs (across consistent regulars, irregulars, and inconsistent regulars) and novel verbs, as some covariates do not apply to novel verbs. Covariate association for picture naming was assessed over all items.

For each analysis in each of the two tasks, all variables that were *either* associated or unbalanced were included in an initial regression model containing the independent and dependent variables of interest for that analysis. Covariates that were not significant in this initial model ($p \geq 0.15$) were dropped, and the model was then re-run with only the remaining covariates to yield the final results. The results reported below were generated by the following regression models and covariates: accuracy of irregulars versus consistent regulars (covariates: age, opposite-class neighborhood strength); accuracy of inconsistent regulars (no covariates); accuracy of novel verbs (whether or not the previous item was a real verb); RTs of irregulars versus consistent regulars (age, performance IQ, item order, stem frequency, past tense length, stem length, verb imageability, and the number of stem-past phonological changes); RTs of inconsistent regulars (age, performance IQ, and item-order); RTs of novel verbs (performance IQ); accuracy of manipulated versus non-manipulated objects (age and full-scale IQ); RTs of manipulated versus non-manipulated objects (age, full-scale IQ, item-order, and object name frequency). For analyses of errors in the past tense production task, the models contained the same covariates as were used in the models for the correct responses (e.g., the model examining RTs of over-regularizations contained the same covariates as the RT model of irregulars versus consistent regulars).

2. Results

2.1. Past tense production

The TS subjects did not differ from the control subjects in accuracy (Table 4) in the production of irregulars (*bring–brought*), inconsistent regulars (*squeeze–squeezed*), over-regularization errors (*bring–bringed*), or regularized (*splim–splimmed*) or irregularized (*splim–splam*) responses to novel verbs. The two groups differed in accuracy only in the production of consistent regular past tenses, for which the TS subjects showed a borderline significant deficit (Table 4) that was also reflected in a significant interaction between verb type (consistent regular versus irregular) and subject group (TS versus control): $F(1,908) = 5.20$, $p = 0.023$.

With respect to response times (Table 5), the TS subjects were significantly faster than control subjects on consistent regulars (*slipped*), over-regularization errors (*bringed*), and regularized responses to novel verbs (*splimmed*), but were not significantly faster on irregulars (*brought*), inconsistent regulars (*squeezed*) and irregularized responses to novel verbs (*splam*). The significant speed increase found on consistent regulars but not irregulars was reflected in a near-significant interaction between verb type (consistent regular versus irregular) and subject group (TS versus control): $F(1,676) = 3.10$, $p = 0.079$.

2.2. Picture naming

For accuracy (Table 6), the TS subjects did not differ from control subjects in naming either manipulated or non-manipulated objects. There was no object type (manipulated versus non-manipulated) by subject group (TS versus control) interaction: $F(1,1018) = 0.01$, $p = 0.907$. In contrast, the two groups did show a difference in their response times (Table 6): The TS subjects responded significantly faster than controls on manipulated objects, but not on non-manipulated objects, with a significant object type by subject group interaction: $F(1,716) = 11.79$, $p = 0.0006$.

3. Summary and discussion

In summary, the children with Tourette's syndrome responded significantly faster than the typically developing

Table 4
Past tense production accuracy and error rates

	Tourette's		Control		
	Means	Adjusted means	Means	Adjusted means	Group difference on adjusted means
Consistent regular (slip)					
Correct (slipped)	93.5% (2.5)	2.95 (0.49)	97.2% (1.3)	4.41 (0.55)	$t(26.8) = 2.04$, $p = 0.051$
Irregularized (slup)	0	–	0	–	–
Unmarked (slip)	3.2% (1.6)	–	0.8% (0.5)	–	–
Inflection (slipping, slips)	0	–	0.8% (0.5)	–	–
Multiple-ed (slippeded)	0.5% (0.5)	–	0	–	–
Double-marked (slupped)	0	–	0	–	–
Other (sli. . .)	2.8% (1.5)	–	1.2% (0.6)	–	–
No Response	0	–	0	–	–
Irregular (bring)					
Correct (brought)	77.1% (9.0)	1.22 (0.42)	69.4% (7.2)	1.40 (0.39)	$t(10.2) = 0.32$, $p = 0.759$
Over-regularized (bringed)	11.0% (4.2)	−2.32 (0.50)	23.0% (6.3)	−1.83 (0.46)	$t(9.2) = 0.78$, $p = 0.456$
Past participle (broke-broken)	1.0% (0.6)	–	0	–	–
Over-irregularized (brung)	1.4% (0.7)	–	3.4% (1.9)	–	–
Unmarked (bring)	4.8% (3.2)	–	1.7% (0.9)	–	–
Inflection (bringing, brings)	0	–	1.3% (1.3)	–	–
Multiple-ed (bringeded)	0	–	0	–	–
Double-marked (broughted)	1.0% (0.6)	–	0	–	–
Other (bing)	3.8% (2.8)	–	1.3% (0.9)	–	–
No Response	0	–	0	–	–
Inconsistent regular (squeeze)					
Correct (squeezed)	93.8% (3.3)	2.50 (0.52)	94.5% (2.5)	2.11 (0.47)	$t(11.6) = 0.59$, $p = 0.564$
Irregularized (squoze)	1.8% (1.2)	–	0.8% (0.8)	–	–
Unmarked (squeeze)	2.7% (2.7)	–	1.6% (1.0)	–	–
Inflection (squeezing, squeezes)	0	–	0	–	–
Multiple-ed (squeezeded)	0	–	0	–	–
Double-marked (squozed)	0	–	0	–	–
Other (sneezed)	1.8% (1.2)	–	3.1% (2.0)	–	–
No Response	0	–	0	–	–
Novel (splim)					
Regularized (splimmed)	68.3% (7.8)	1.07 (0.42)	76.6% (3.2)	1.49 (0.41)	$t(11.6) = 0.81$, $p = 0.435$
Irregularized (splam)	18.8% (5.4)	−2.22 (0.58)	10.5% (3.7)	−3.12 (0.57)	$t(11.3) = 1.26$, $p = 0.232$
Unmarked (splim)	2.2% (1.8)	–	1.6% (0.8)	–	–
Inflection (splimmimg)	0	–	0	–	–
Multiple-ed (splimmeded)	0	–	0	–	–
Double-marked (splammed)	0.9% (0.6)	–	0.4% (0.4)	–	–
Other (spimmed)	9.8% (2.7)	–	9.4% (4.5)	–	–
No Response	0	–	1.6% (1.2)	–	–

Note: Mean percentages are computed for each subject and then averaged over subjects. Standard errors are shown in parentheses. Percentages may not add up to 100% due to rounding. Because hierarchical logistic regression models may be inaccurate with very small sample sizes, *t*-statistics from hierarchical logistic regressions are shown only for comparisons in which the response-type constituted at least 10% of responses in both subject groups. See text for the covariates contributing to the adjusted means. Adjusted accuracy means (and standard errors) from the logistic regressions are presented as untransformed values. These can be transformed into probabilities of correct responses or errors with the equation $y = 1/(1 + e^{-x})$, where x is the adjusted mean. Transformed probabilities are not shown here because standard errors are not transformable. Note that adjusted means of zero would be transformed to a probability of 0.5; larger values in the positive direction will transform to a probability that approaches 1; larger values in the negative direction will transform to a probability approaching 0. See text for definitions of error types.

control children when producing past tenses of consistent regular verbs (*slip–slipped*), regularized past tenses of novel verbs (*splim–splimmed*), over-regularization errors to irregular verbs (*bring–bringed*), and when naming pictures of manipulated objects (*hammer*). In contrast, the children with TS were not significantly faster than controls (though this difference approached significance in some cases) when producing the past tenses of irregular and inconsistent regular verbs (*bring–brought*, *squeeze–squeezed*), when producing irregularized past tenses of novel verbs (*splim–splam*), and when naming pictures of non-manipulated objects (*elephant*). Significant or near-significant interactions between subject group and item type (for both consistent regular versus irregular verbs, and manipulated versus non-manipulated objects) reflected these differential response times. Accuracy did not differ between the subject groups in any condition in either past tense production or picture naming with the exception of consistent regulars, on which the TS children were borderline significantly less accurate.

This pattern of results does not appear to be explained by various potentially confounding subject-level factors, including age, full-scale IQ, verbal IQ, and performance IQ. Nor does it seem to be accounted for by a wide range of item-level factors,

Table 5
Past tense production response times

Response Type	Tourette's		Control		Group difference on adjusted means
	Means	Adjusted means	Means	Adjusted means	
Correct consistent regular (slipped)	7.39 (0.04)	7.49 (0.13)	7.85 (0.03)	7.92 (0.12)	$t(11.4) = 2.41$, $p = 0.034$
Correct irregular (brought)	7.36 (0.04)	7.32 (0.13)	7.83 (0.04)	7.66 (0.13)	$t(11.8) = 1.85$, $p = 0.089$
Over-regularized irregular (bringed)	7.39 (0.04)	7.40 (0.11)	7.80 (0.03)	7.80 (0.10)	$t(11.0) = 2.53$, $p = 0.028$
Correct inconsistent regular (squeezed)	7.59 (0.07)	7.54 (0.13)	7.86 (0.05)	7.92 (0.12)	$t(11.1) = 2.08$, $p = 0.062$
Regularized novel (splimmed)	7.59 (0.05)	7.56 (0.14)	8.08 (0.04)	8.14 (0.13)	$t(11.9) = 2.95$, $p = 0.012$
Irregularized novel (splam)	8.02 (0.06)	7.97 (0.16)	8.05 (0.11)	8.39 (0.20)	$t(9.5) = 1.65$, $p = 0.131$

Note: Standard errors are shown in parentheses. Response time analyses were performed only on response types which constituted at least 10% of responses of both subject groups, ensuring a sufficient number of response times for analysis.

including the presentation order of the items, characteristics of the first phoneme of the response, various measures of word frequency and word length, and, for past tense production, verb imageability, phonological neighborhood measures, consistent rime voicing, stem-past phonological changes, and three different measures of potential bias based on the nature of the previously presented verb.

It is also unlikely that the data can be explained by other factors that were not directly controlled for. First, motor or reading abnormalities seem unlikely to explain the pattern of results, since a range of factors that could reflect such abnormalities, or could potentially lead to differential performance across items as a result of such abnormalities, were controlled for (e.g., measures of IQ, phonological complexity, word frequency, and imageability). Second, comorbid disorders do not seem to explain the findings, given that only two TS subjects had any comorbidities (two with ADHD, one of whom also had OCD). Third, the results do not appear to be accounted for by psychoactive medications, given that not all subjects were taking these drugs, there was variability regarding which drugs were taken, and previous evidence suggests that medication typically taken in TS does not influence neuropsychological performance (Bornstein & Yang, 1991; Johannes, 1999). Finally, a general speed–accuracy trade-off among the TS children does not seem to account for the data, since the TS children were not less accurate than control children on every condition in which they were faster (e.g., manipulated objects, regularized past tenses of novel verbs).

It is also unclear how the data could be explained by "single-mechanism" models of morphology, which posit that both idiosyncratic and rule-governed linguistic knowledge depend on a single computational system. On a single-mechanism perspective, abnormalities in regular (as compared to irregular) English past tense inflection can be explained by the general tendency for regular past tense forms to be more phonologically complex (e.g., *walked* versus *dug*) (Bird, Lambon Ralph, et al., 2003; Joanisse & Seidenberg, 1999; McClelland & Patterson, 2002). However, various measures of phonological complexity, including stem and past tense phonological length, consistency of the rime voicing of the past tense form, and the number of stem-past phonological changes, were controlled for. Moreover, to our knowledge previous single-mechanism claims and simulations have only examined a regular *deficit* in *accuracy*; it is not clear how such models might explain the *speeded* performance observed here. Finally, such an account also does not seem to explain the difference observed between manipulated and non-manipulated object names (for which phonological length differences were also controlled).

Instead, the results from both the past tense production and picture naming tasks seem consistent with the hypothesis that Tourette's syndrome is associated with abnormal procedural memory, specifically resulting in faster-than-normal response times for responses whose processing depends upon the procedural system.

Thus in the past tense production task response times were significantly speeded in TS (as compared to controls) in all and only those cases where the grammatical/procedural system is expected to be engaged in *-ed*-affixation: consistent regular past tenses (*slipped*), regularized novel past tenses (*splimmed*),

Table 6
Picture naming accuracy and response times

	Tourette's		Control		Group difference on adjusted means
	Means	Adjusted means	Means	Adjusted means	
Accuracy					
Manipulated	81.6% (6.0)	1.94 (0.34)	84.0% (2.5)	1.97 (0.35)	$t(16.4) = 0.07$, $p = 0.948$
Non-manipulated	81.6% (3.8)	1.89 (0.35)	83.6% (3.1)	1.87 (0.34)	$t(16.1) = 0.04$, $p = 0.970$
Response Time					
Manipulated	7.01 (0.03)	7.03 (0.07)	7.32 (0.03)	7.36 (0.07)	$t(13.3) = 3.24$, $p = 0.006$
Non-manipulated	7.08 (0.03)	7.07 (0.07)	7.21 (0.03)	7.24 (0.07)	$t(13.4) = 1.64$, $p = 0.124$

Note: Mean percentage correct scores and mean response times are computed for each subject and then averaged over subjects. Standard errors are shown in parentheses. See text for the covariates contributing to the adjusted means. Adjusted accuracy means (and standard errors) from the logistic regressions are presented as untransformed values. See Table 4 for discussion of transformations of these values to probabilities.

and over-regularization errors (*bringed*). Indeed, the latter two types of response are highly unlikely to have been memorized, and therefore, on a dual-system view, should be computed by the grammar. In contrast, no significant speeding of response times was found for those forms whose processing is expected to depend on lexical/declarative memory—that is, irregular past tenses (*brought*), inconsistent regular past tenses (*squeezed*), and irregularized novel past tenses (*splam*).

Interestingly, the data suggest that the speed increase when producing -*ed*-affixed forms (but *not* when naming manipulated objects; see below) tends to be accompanied by somewhat of an accuracy decrease when producing these particular forms. Thus the TS children were borderline significantly less accurate than the control children at past tense production of consistent regulars, and showed non-significantly lower accuracy rates at regularizing novel verbs and at over-regularizing irregulars. In contrast, the TS children did not show lower production rates at irregular past tenses, inconsistent regular past tenses, and irregularizations of novel verbs; indeed they showed non-significantly *higher* rates in some cases (see adjusted as well as unadjusted means in Table 4).

The decreased accuracy that seems to accompany the increased speed of -*ed*-affixed forms might be explained by the abnormal rapidity of the computation of these forms, which could result in errors such as failed affixation (*slip*) or excessive (i.e., unsuppressed or “hyper”) affixation (*slippeded*) affixation. Indeed, the decrease in accuracy on consistent regulars in TS was largely explained by higher rates of both of these forms (though these error rates were not analyzed statistically; see Section 1)—a very similar pattern to that observed in Huntington’s disease, in which unsuppressed “hyper” motor and other behaviors are also found (Ullman, in press-a; Ullman et al., 1997). Evidence for unsuppressed affixation was also observed in the production of double-marked forms such as *bring–broughted* and *splim–splammed*. The TS children produced four such forms, as compared to only one such error among the controls—again, a similar pattern to Huntington’s disease.

As in past tense production, in the picture naming task those items that depend on procedural memory – manipulated objects – were produced significantly faster by the TS than control children, while those items that do not depend on procedural memory – non-manipulated items – were not. Interestingly, and unlike in past tense production, in picture naming there were no group differences whatsoever in accuracy, for either manipulated or non-manipulated objects. The TS subjects’ normal accuracy does not appear to be due to ceiling effects, since accuracy in both conditions was in the range of 80–85%, well below 100%, while by contrast significant group differences were found for consistent regular past tenses, where both groups performed above 90%. It is not yet clear what accounts for the preserved accuracy of naming manipulated forms in the face of somewhat impaired production rates of -*ed*-affixed forms. However, it could plausibly be explained by the fact that the involvement of the procedural system is expected to take place at very different levels in the two tasks. Whereas in past tense production the system underlies -*ed*-affixation, whose disruption can easily lead to response errors, in picture naming it primarily underlies the (manipulation) knowledge associated with the word, rather than the production of the word itself.

Despite the finding that in both tasks only forms hypothesized to depend on procedural memory showed significant speeding in TS (relative to control subjects), and moreover these forms showed significantly or near-significantly more speeding than their matched non-procedural conditions (e.g., manipulated versus non-manipulated objects), it is not the case that other forms showed no signs of speeding at all. In every condition for which response times were reported (Tables 5 and 6) the TS subjects were at least somewhat faster than controls, with this difference approaching significance ($p < 0.10$) in two conditions (irregular and inconsistent regular past tenses), and suggestive ($p < 0.15$) in the other two (irregularized novel past tenses and non-manipulated objects).

This pattern may be explained by a combination of one or more factors—assuming that these non-significant differences are taken to reflect weak but real effects. First, speeding of grammatical/procedural processes in TS would be expected to affect not only regular morpho-phonology (*walk* + -*ed*) but also other aspects of the mental grammar, including morpho-syntax (e.g., in the computation of Tense). Since all inflection should depend on morpho-syntax (independent of the inflected forms’ morpho-phonology; Steinhauer & Ullman, 2002; Ullman et al., 2005; Ullman & Pierpont, 2005), all inflection should be at least somewhat speeded up. The greater speed increase observed for -*ed*-affixed than for lexically based forms may thus be explained by *additional* effects (i.e., the morpho-phonological -*ed* affixation process), on top of morpho-syntax (Steinhauer & Ullman, 2002; Ullman et al., 2005; Ullman & Pierpont, 2005).

However, morpho-syntax cannot account for the (albeit only statistically suggestive) speed increase of non-manipulated objects. Both this speed increase and the speed-up of lexically based inflected forms can instead or additionally be explained by evidence suggesting that whereas some portions of the basal-ganglia (likely projecting to BA 44 and premotor cortex) subserve procedural memory, other portions (likely projecting to BA 45/47) subserve lexical/declarative retrieval (Ullman, 2004, 2006a). On this view, the frontal/basal-ganglia abnormalities in TS lead to unsuppressed and/or speeded application of all functions that depend on abnormal portions of frontal/basal-ganglia circuits. The lack of significant speed increases among lexically based inflected forms and non-manipulated objects may be explained by the testable hypothesis that in TS there tend to be greater abnormalities in those portions of frontal/basal-ganglia circuits that subserve motor function and procedural memory than those portions that underlie lexical/declarative retrieval. Indeed, this hypothesis seems consistent with the fact that motor tics are far more prevalent in TS than are vocal tics (Singer, 2005).

Finally, the partially speeded performance observed on items not hypothesized to depend on procedural memory may also or instead reflect speed increases of certain other functions. For example, phonological processing, which is also posited to depend on the grammatical/procedural system (Ullman, 2004; Ullman & Pierpont, 2005), could also be speeded in

TS, potentially affecting the production of all linguistic forms in both tasks, independent of any additional speeding due to procedurally based processing. Alternatively, all responses may be at least somewhat affected by speed increases in aspects of motor programming, or perhaps in perceptual or cognitive processes involved in both tasks.

This study leads to several interesting issues for future investigation. First, although speed increases were found in two tasks that probed procedural memory in very different ways, it remains to be seen whether other tasks probing processing or even learning in procedural memory show similar speed increases. Similarly, future studies should examine whether morpho-syntax, phonology, lexical retrieval or other language functions thought to depend on procedural memory or (other) frontal/basal-ganglia circuits are also speeded up, and to what relative degree. More generally, it seems crucial for studies of TS to measure not only response *accuracy* but also response *time*, a dependent variable that has been largely ignored in previous studies of language in TS.

The possibility that lexical memory, and perhaps other aspects of declarative memory as well, may be not only spared, but perhaps even somewhat enhanced in TS, should also be further investigated. Such an enhancement would be consistent with the slightly *higher* TS accuracy of lexically dependent past tense forms, as compared to control children (see above). A declarative memory enhancement could be explained by abnormalities of procedural memory, since independent evidence suggests that the dysfunction of procedural memory can lead to an increase in declarative memory functionality (Ullman, 2004). Indeed, evidence suggesting such a "see-saw effect" (Ullman, 2004) has been found in autism, another developmental disorder in which procedural memory may be abnormal (Ullman, 2004; Walenski, Mostofsky, Larson, & Ullman, submitted for publication; Walenski et al., 2006).

In conclusion, the study reported here suggests that the processing of previously acquired procedural but not declarative knowledge is particularly speeded in Tourette's syndrome. This pattern seems to hold for very different types of procedurally based knowledge, that is, of grammar and manipulated objects. The procedural speeding appears to be accompanied by a slight decrease in accuracy in the production of *-ed*-affixed forms, and by errors such as *slippeded* and *broughted*. These errors, which are consistent with unsuppressed affixation, are also found in Huntington's disease, an adult-onset disorder also associated with unsuppressed behaviors. The results strengthen the view that in both adult-onset and developmental disorders of the basal ganglia, abnormalities thought to involve increased or decreased inhibition of frontal activity leading to "hypo" or "hyper" behaviors (see above and Jankovic & Tolosa, 2007) similarly affect rule-governed composition in language. This is consistent with the hypothesis that rule-governed composition depends primarily on frontal regions of the procedural system, whereas the basal ganglia themselves may be more important in other functions, in particular in the procedural learning of rule-governed knowledge (Ullman, 2006a, in press-b) (as well as in other, non-procedural, functions such as late syntactic integration; Friederici, Kotz, Werheid, Hein, & von Cramon, 2003). Importantly, the data also suggest that the frontal/basal-ganglia abnormalities in Tourette's syndrome may lead not only to tics but also to a wider range of unsuppressed and rapid behaviors, including the cognitive processing of rule-governed forms in language and other types of procedural knowledge. Finally, a number of new issues and interesting questions are raised by this study, leading to testable hypotheses that can be investigated in future experiments.

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