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Inflectional morphology in high-functioning autism: Evidence for speeded grammatical processing

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ABSTRACT

Autism is characterized by language and communication deficits. We investigated grammatical and lexical processes in high-functioning autism by contrasting the production of regular and irregular past-tense forms. Boys with autism and typically developing control boys did not differ in accuracy or error rates. However, boys with autism were significantly faster than controls at producing rule-governed past-tenses (*slip-slipped*, *plim-plimmed*, *bring-bringed*), though not lexically dependent past-tenses (*bring-brought*, *squeeze-squeezed*, *splim-splam*). This pattern mirrors previous findings from Tourette syndrome attributed to abnormalities of frontal/basal-ganglia circuits that underlie grammar. We suggest a similar abnormality underlying language in autism. Importantly, even when children with autism show apparently normal language (e.g., in accuracy or with diagnostic instruments), processes and/or brain structures subserving language may be atypical in the disorder.

1. Introduction

Autism is a developmental disorder of the brain that is strongly associated with deficits in language and communication (APA, 1994). Language impairments are consistently found in pragmatics (the knowledge required to use and interpret language appropriately in social and real world contexts), even in high functioning individuals. In contrast, performance at tasks involving single words, in both receptive and expressive domains, does not show consistent impairments, and in some individuals may be spared or even enhanced in some respects relative to typically developing controls (Lord & Paul, 1997; Luyster and Lord, 2009; Minshew, Goldstein, & Siegel, 1997; Norbury, Griffiths, & Nation, 2010; Walenski, Mostofsky, Gidley-Larson, & Ullman, 2008; Walenski, Tager-Flusberg, & Ullman, 2006).

The status of grammar is less clear. Grammar subsumes the knowledge required to combine words (i.e., syntax) and parts of words (i.e., morphology) into sequentially and hierarchically rule-governed structured units. Performance consistent with deficits in these areas has been widely reported in autism, for both expressive and receptive language tasks, in both auditory and visual (i.e., reading) domains (see below and Boucher, 2012; Eigsti & Bennetto, 2009; Eigsti, Bennetto, & Dadlani, 2007; Perovic, Modyanova, & Wexler, 2012; Walenski et al., 2006; Williams, Botting, & Boucher, 2008). However, not all individuals

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show these deficits, and some show no apparent grammatical impairments at all, at least with standardized assessments (Kjelgaard & Tager-Flusberg, 2001; Minshew et al., 1997).

Consistent with this heterogeneity, a structural MRI study reported atypical volumes of language areas in the brains of individuals with autism who have language impairments, but not in those who do not (De Fossé et al., 2004). Nevertheless, functional imaging studies of sentence comprehension have revealed atypical activation patterns in autism relative to control participants, even when the groups did not differ in accuracy (Just, Cherkassky, Keller, & Minshew, 2004; Kana, Keller, Cherkassky, Minshew, & Just, 2006; Müller et al., 1998, 1999). In addition, in one such study with typical accuracy but atypical activation patterns in autism, the adults with autism also responded more quickly than their matched controls (Just et al., 2004).

Overall, the data suggest that accuracy alone may be too crude to detect atypical language processing in many individuals with autism – that is, even if language output appears normal, the underlying processes that created that output may be different in autism, for example in speed (e.g., processes used by individuals with autism may be slower or even faster than in typical individuals), or perhaps in kind (i.e., different processes may be used altogether).

The main aim of the current study is to investigate language in autism using a paradigm that allows us to examine both the accuracy and timing of both grammatical and lexical processes, while holding other factors constant: that is, the production of regular and irregular inflected forms. This fills an important gap, since little research has examined regular and irregular morphology in autism, despite the theoretical importance of this distinction.

1.1. Inflectional morphology

Few studies have investigated the production of inflectional morphology (changes or additions to a word to reflect its correct use in context) in autism, including in the contrast between regular and irregular inflected forms (e.g., *walked* vs. *dug* in English past tense), which may reflect different underlying processes (see below).

First of all, several studies of elicited verb production in children with autism have reported an increased number of incorrect verb forms in contexts that require the past tense (e.g., saying *play* instead of *played*) (Bartolucci & Albers, 1974; Botting & Conti-Ramsden, 2003; Seung, 2007), as well as in contexts that require the present tense (e.g., saying *walk* instead of *walks*) (Roberts, Rice, & Tager-Flusberg, 2004). In addition, in samples of spontaneous speech produced while children interacted with a parent, children with autism aged 8–10 years old have produced correct regular and irregular inflectional morphemes (past tense and present tense) at different rates than typically developing individuals or mental-age-matched control participants with intellectual disability (Bartolucci, Pierce, & Streiner, 1980; Howlin, 1984).

Only one study we are aware of has separately reported performance on regular and irregular forms in autism. This study, which included children with autism across a wide age range (5–15 years) and IQ range (42–141), examined verb forms elicited in response to pictures (Roberts et al., 2004). Language-impaired children with autism – defined as those individuals scoring below 70 on the Peabody Picture Vocabulary Test (PPVT-III; Dunn & Dunn, 1997), a test of receptive vocabulary – were compared against age-matched groups of children with autism who were either unimpaired or borderline impaired on the PPVT. The language-impaired group produced fewer correct regular and fewer correct irregular past tense forms, with more unmarked errors on both (*walk-walk*; *dig-dig*), relative to both the unimpaired and borderline-impaired language groups. However, it is not clear whether the regular and irregular deficits in the language-impaired group reflect a single dysfunction affecting both types of forms (e.g., a deficit of morphosyntax) or two distinct areas of dysfunction, one affecting regulars and one irregulars. Moreover, performance at regulars and irregulars was not statistically compared, and no non-autistic control participants were included, so it is not clear if either of the latter groups might have also had some impairment at either or both regular and irregular forms. Note also that the task included only a small number of regular and irregular test items (11 regular, 8 irregular), which were not reported to be matched on length, frequency, or any other factors which may influence how difficult the forms are to produce.

Impairments have thus consistently been reported at the production of inflected forms, though several factors potentially limit the interpretation of these findings. First, all prior production studies collected data in contexts that required social interaction (e.g., with a parent for collecting spontaneous speech samples or an experimenter for elicited production). It may be that this social context contributed to their poor performance (Ozonoff & Strayer, 2001). Second, rigorous diagnostic measures of autism were not developed until the late 1980s and early 1990s (Eigsti et al., 2007), making older studies difficult to evaluate in comparison to more recent findings. Third, no prior study has examined production response times, so more subtle abnormalities at producing either regular or irregular forms may be present even if all forms are ultimately produced correctly. Finally, only one study reported results for regular and irregular forms separately, but these forms were not matched, were not statistically compared, and moreover the individuals with autism were not compared with a typically developing control group.

1.2. Theories and predictions

The dearth of studies contrasting regular and irregular inflected forms in autism is a particularly important lacuna, as these forms are posited by various theoretical perspectives to rely on different cognitive processes and on different brain structures, underscoring the need to examine their production separately. Indeed, the regular/irregular distinction lies at the heart of a long-standing debate in the study of language and cognition (Bird, Lambon Ralph, Seidenberg, McClelland, &

Patterson, 2003; Clahsen, 1999; Joanisse & Seidenberg, 1999; McClelland & Patterson, 2002a, 2002b; Oh, Tan, Ng, Yeh, & Graham, 2011; Pinker, 1999; Pinker & Prince, 1988; Pinker & Ullman, 2002a, 2002b; Rumelhart & McClelland, 1986). Here we summarize the two main opposing theoretical perspectives, and lay out possible predictions for autism.

One theoretical perspective, embodied in dual-system models of language, assumes a fundamental distinction between the ''mental lexicon'' and the ''mental grammar'' (Pinker, 1999; Pinker & Ullman, 2002b). It has been posited that these two language capacities depend on two brain memory systems, with the mental lexicon being learned in declarative memory, which is rooted in temporal lobe structures, while the mental grammar depends largely on procedural memory, which is rooted in frontal/basal-ganglia structures (Ullman, 2001, 2004; Ullman et al., 1997).

On such dual-system views, the mental lexicon is a repository of stored information, including all idiosyncratic word-specific information. This encompasses the arbitrary sound-meaning pairings of non-compositional words like *cat*, as well as what irregular (unpredictable) morphological forms a word may take (e.g., *dig* takes *dug* as its past-tense form). The mental lexicon is not simply a rote memory store, but rather depends on associative memory, and can generalize patterns from already-stored forms to new ones (e.g., from *sing-sang*, *spring-sprang* to the novel irregular *spling-splang*) (Pinker & Ullman, 2002a).

The mental grammar underlies the rule-governed combination of smaller linguistic elements (e.g., phonemes, morphemes, words) into larger sequentially and hierarchically structured units such as syllables, phrases, sentences, and complex words such as *walked*. Real and novel ''consistent'' regular past tenses (i.e., verbs whose stems are not phonologically similar to the stems of existing irregular verbs; e.g., *walked*, *blicked*) are posited to be generally computed by the mental grammar, which combines word bases (e.g., *walk*) with affixes (e.g., –*ed*). This grammatical combination is a default process, and applies to any form for which the associative memory system cannot produce an acceptable output, whether because it fails to retrieve a memorized form (e.g., *sang*) or fails to generalize to a novel form (e.g., *splang*).

In the production of a past tense form, a search for a stored inflected form in the lexicon operates in parallel with application of the grammatical rule to add the default –*ed* suffix to the stem, with the lexical search inhibiting the rule as they both proceed. If the search succeeds, and a past tense form is retrieved from the lexicon, the rule-based output is blocked. If an inflected form is not retrieved from the lexicon, the rule-based output is produced. The concept of blocking underlies the claim that the past tenses of regular verbs whose stems are phonologically similar to those of irregular verbs (e.g., *glide-glided*) are stored in memory like irregulars (and are therefore predicted to pattern with irregulars): storage of these ''inconsistent'' regular past tense forms prevents their irregularization, e.g., *glide-glode* or *glide-glid*, cf. *ride-rode* or *hide-hid* (Ullman, 1993, 2001). If this were not the case, the attempt to create an irregular by analogy (*glid*) would block the rule-based regular production (*glided*), preventing such forms from ever being produced (Pinker, 1999; Pinker & Ullman, 2002b; Ullman, 2001).

The Procedural Deficit Hypothesis of autism, which grew out of this dual-system theory of language, posits that abnormalities in both language and motor domains in autism reflect, at least in part, abnormalities of the neural structures that underlie the procedural memory system, such as the basal ganglia and frontal cortex (Mostofsky, Goldberg, Landa, & Denckla, 2000; Ullman, 2004; Walenski et al., 2006). Since autism has been associated with abnormalities of these brain structures (Amaral, Schumann, & Nordahl, 2008), atypical production of regular forms might be expected. Just as impaired basal ganglia function may lead to suppressed (e.g., in Parkinson's disease) or unsuppressed (e.g., in Huntington's disease or Tourette Syndrome) motor functions, such impairments may also lead to suppressed or unsuppressed language and cognitive functions that also depend on these structures (Ullman, 2004; Walenski, Mostofsky, & Ullman, 2007). Thus atypical production might manifest in different ways, depending on the nature of the basal ganglia abnormality – for example as reduced accuracy, and potentially either slowed (suppressed) or speeded (unsuppressed) response times for regular past tenses. Indeed, prior studies of language and motor function in autism suggest that both speeded and slowed response times are possible (Just et al., 2004; Mari, Castiello, Marks, Marraffa, & Prior, 2003; Walenski et al., 2006). Faster-than-typical responses have been seen in a sentence comprehension task (Just et al., 2004), as well as for high-functioning individuals in a reaching-to-grasp task, while in the same task low-functioning individuals exhibited slower-than-typical responses (Mari et al., 2003). Thus high-functioning individuals may be more prone to faster-than-normal response times than low-functioning individuals, who may be given to slowed responses.

A second theoretical perspective of regular and irregular forms posits that the processing of all inflected forms depends on associative pattern matching (Bybee, 1985; Joanisse & Seidenberg, 1999; McClelland & Patterson, 2002a; Rumelhart & McClelland, 1986; Seidenberg, 1997). One such account, while relying on a single computational mechanism, nonetheless makes explicit predictions regarding dissociations between regular and irregular inflected forms and the brain regions they depend on (Joanisse & Seidenberg, 1999; McClelland & Patterson, 2002a; Patterson, Lambon Ralph, Hodges, & McClelland, 2001). On this view, the production of irregular past tenses depends particularly on word meanings that rely on temporal-lobe cortical regions, whereas the production of regular and novel past tenses is posited instead to show a greater reliance on phonology and frontal lobe regions. The greater reliance of morphologically regular forms on phonology is argued to follow, at least in part, from the claim that these regular forms are more phonologically complex than morphologically irregular forms (Bird, Lambon Ralph, et al., 2003). A similar claim maintains that (at least some) regular morphological forms are phonologically irregular in English, and are therefore more difficult (e.g., *beeped*, which has a long vowel followed by a consonant cluster, violates phonological constraints on syllable size; *whipped*, with a short vowel followed by a cluster, does not). In contrast, many (though not all) morphologically irregular forms are phonologically regular (e.g., *kept* does not exceed limitations on syllable size, though *sold* does) (Burzio, 2002). For either reason then, the production of (often complex) regular inflected forms is predicted to place a generally greater burden on phonological processing than the production of the phonologically simpler irregulars. With respect to autism, while some phonological deficits have been observed in the disorder (Shriberg et al., 2001), there is also evidence for enhancements of aspects of phonologically related functions, including the learning of phonological forms and the processing of pitch contours of sentences (Järvinen-Pasley, Wallace, Ramus, Happé, & Heaton, 2008; Norbury et al., 2010).

These different theoretical perspectives therefore make empirically distinguishable predictions. According to dual-system views and the Procedural Deficit Hypothesis, high-functioning autism should be associated with relative sparing of lexically represented inflected forms (whether irregulars or inconsistent regulars), but abnormal production of regularly inflected forms that depend on rule-governed composition and procedural memory. Importantly, this abnormality may potentially manifest in different ways, including in lower accuracy, or slower or even faster response times. In contrast, the single-mechanism model discussed here posits that previously observed differences between regular and irregular forms reflect (uncontrolled) differences in phonological complexity. Therefore, if this view is correct, then controlling for phonological complexity should obviate any such differences (Bird, Lambon Ralph, et al., 2003).

1.3. The present study

In the present study we examine the production of inflected forms in autism in light of these methodological and theoretical issues, using a well-studied task that contrasts carefully controlled regular (e.g., *step-stepped*) and irregular past tenses (e.g., *sweep-swept*). All stimuli were presented by computer, limiting the social requirements of the task. We measured both accuracy and response times at the production of these inflected forms in a group of high-functioning boys with autism (aged 7–13) and a group of matched typically developing boys.

2. Method

2.1. Participants

Twenty high-functioning boys with autism participated in this study (Table 1). We focused on boys because autism has a much higher prevalence in boys (Lord & Spence, 2006), and because prior work suggests sex differences in the processing of language (Ullman, Miranda, & Travers, 2008; Walenski et al., 2008). Diagnosis of autism was based on DSM-IV criteria and confirmed using both the Autism Diagnostic Interview-Revised (ADI-R) and the Autism Diagnostic Observation Schedule-Generic (ADOS-G) (Lord et al., 2000; Lord, Rutter, & Le Couteur, 1994). No children had an identifiable cause of autism (e.g., Fragile X syndrome), or presence or history of a definitive neurologic disorder including seizures (except for uncomplicated brief febrile seizures), tumor, severe head injury, stroke, lesion, or disease; presence of a severe chronic medical disorder; a major visual impairment; or childhood schizophrenia or psychosis. Participants with diagnoses of disorders that are common comorbidities with autism were included in the study. These include attention-deficit hyperactive disorder (ADHD; $n = 2$ participants), obsessive–compulsive disorder (OCD; $n = 2$) and both ADHD and OCD ($n = 1$).

Nine of the 20 participants with autism were taking psychoactive medication: one was taking divalproex; 1 paroxetine and methylphenidate; 1 citalopram, buspirone, and buproprion; 1 sertaline and mixed amphetamine and dextroamphetamine; 1 atomoxetine and fluoxetine; 1 sertraline; 1 methylphenidate, paroxetine, and risperidone; 1 methylphenidate; and 1 fluoxetine. Children were not taken off medication for testing, and the effects of medication on performance were not evaluated, as not all participants were taking medication, and there was variability regarding which drugs were being taken and when they might have been taken last.

In addition to the participants with autism, we tested 25 typically developing (TD) control boys selected for similar handedness, age, education, IQ scores, and reading ability (Table 1). Note that the two groups differed nonetheless on education and IQ scores; see below for discussion of statistical control of these and other variables. The control participants were free of any language, developmental or psychiatric disorders, based on DICA-IV criteria (Reich, Welner, & Herjanic, 1997), and did not have immediate family members with autism.

Table 1
Participant characteristics.

	Autism	Typically developing (TD)	Group differences
N	20	25	
Sex	All male	All male	
Handedness	16R (3L/1M)	23R (0L/2M)	Fisher's exact, $p = 0.38$
Age (years)	10.8 (1.8)	10.3 (1.3)	$t(43) = 1.11$, $p = 0.27$
Education (years)	5.57 (1.5)	4.50 (1.3)	$t(32) = 2.24$, $p = 0.03$
FSIQ	107.0 (14.8)	117.5 (10.7)	$t(43) = 2.76$, $p = 0.008$
Verbal IQ	111.0 (19.5)	119.2 (16.5)	$t(42) = 1.63$, $p = 0.11$
Performance IQ	104.8 (16.3)	114.7 (11.5)	$t(42) = 2.36$, $p = 0.02$
WIAT-R	110.9 (13.0)	112.0 (10.6)	$t(38) = 0.29$, $p = 0.77$

Note: Means (and standard deviations) are shown for continuous variables (imputed values for education are not included). *T*-tests are two-sample, equal variance. R, right-handed; L, left-handed; M, mixed handedness.

All participants were native English speakers, aged 7–13. The majority were right-handed, with a few left or mixed (M) handed participants (Table 1). Due to the high prevalence of left- and mixed-handed individuals in autism (Soper et al., 1986; Tsai, 1983), non-right-handedness was not an exclusionary criterion. All participants had full scale IQ (FSIQ) scores greater than 80, unless there was a 12 point or greater verbal and performance IQ discrepancy, in which case the higher of the two was greater than 80 and the lower of the two was greater than 70 (FSIQ range 78–139). IQ for all participants was assessed using the Wechsler Intelligence Scale for Children (WISC-3 or WISC-4), except for two participants with autism: one who was given the Wechsler Abbreviated Scale of Intelligence (WASI) and another who was given the Differential Ability Scale (DAS). To ensure that participants would be able to read the stimuli, reading level was assessed using the Wechsler Individual Achievement Test, Revised (WIAT-R); children were not run on the past-tense production task if their Word Reading subtest score was below 80 (range: 87–134; scores were missing from 1 control and 4 participants with autism, who were not excluded, but reported no difficulty reading the stimuli). An additional four boys with autism and three control boys were enrolled in the study, but did not complete the past-tense production task; these are not included in Table 1. Children with autism were recruited from the Center for Autism and Related Disorders at the Kennedy Krieger Institute, and through the Autism Society of America. Control children were recruited through community wide service groups and volunteer organizations (e.g., Cub Scouts, Brownies), through parents of those already participating, and through friends and associates of staff members at the Kennedy Krieger Institute and Georgetown University. 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 testing began, and received a copy of the consent form.

2.2. Past tense production task

Participants were asked to produce the past tenses of verbs presented in written sentence contexts (Prado & Ullman, 2009; Walenski et al., 2007). Five types of verbs were presented (Tables 2 and 3): 32 consistent regulars (i.e., regulars whose stems are not phonologically similar to existing irregulars; e.g., *step-stepped*) matched (see just below) to 32 irregulars (e.g., *sweep-swept*); 16 inconsistent regulars (i.e., regulars whose stems are phonologically similar to existing irregulars; e.g.,

Table 2
Verb stems and correct responses (for real verbs) in the past tense production task.

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

Note: As in other studies with the same version of the past-tense production task (Prado & Ullman, 2009; Walenski et al., 2007), three problematic verbs were excluded from all analyses (marked with '*'): *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 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).

Table 3
Properties of verbs in the past-tense production task.

Measure	Consistent regular	Irregular	Regular/irregular difference	Inconsistent regular	Novel regular	Novel irregular
n	31	30		16	16	16
Fricative onset	14 yes/17 no	15 yes/15 no	Fisher's exact, $p = 0.80$	6 yes/10 no	3 yes/13 no	10 yes/6 no
Past tense frequency	5.86 (2.00)	5.75 (2.13)	$t(59) = 0.21$, $p = 0.83$	4.48 (1.62)	–	–
Stem frequency	5.69 (1.93)	5.74 (2.24)	$t(59) = 0.09$, $p = 0.93$	4.68 (1.71)	–	–
Past tense length (phonemes)	4.23 (0.67)	4.03 (0.61)	$t(59) = 1.17$, $p = 0.25$	4.88 (1.09)	4.38 (0.62)	5.56 (0.73)
Stem length (phonemes)	3.19 (0.65)	3.70 (0.65)	$t(59) = 3.03$, $p = 0.004$	3.75 (0.93)	3.38 (0.62)	4.44 (0.63)
Verb imageability	3.50 (0.76)	3.59 (0.68)	$t(59) = 0.51$, $p = 0.61$	3.46 (0.89)	–	–
Same-class neighborhood	10.20 (0.46)	−0.26 (8.64)	$t_s(29.2) = 6.52$, $p < 0.0001$	9.89 (0.26)	9.91 (0.75)	9.81 (0.25)
Opposite-class neighborhood	10.07 (3.14)	9.82 (0.27)	$t_s(30.4) = 0.44$, $p = 0.66$	10.25 (1.19)	8.32 (4.42)	10.7 (0.66)
Coda Consonants	1.48 (0.51)	1.40 (0.50)	$t(59) = 0.65$, $p = 0.52$	1.75 (0.45)	1.56 (0.51)	1.94 (0.44)
Consistent rime voicing	31 yes	21 yes/9 no	Fisher's exact, $p = 0.0008$	16 yes	16 yes	16 yes
Stem-past changes	1.00 (0)	1.47 (0.51)	$t_s(29) = 5.04$, $p < 0.0001$	1.13 (0.34)	1.00 (0)	1.13 (0.34)
Phonological irregularity	6 yes/25 no	2 yes/28 no	Fisher's exact, $p = 0.26$	8 yes/8 no	3 yes/13 no	9 yes/7 no

Note: Means (and standard deviations) are provided for continuous variables. One consistent regular and two irregulars were excluded prior to analysis (see note to Table 2), leaving 31 and 30 respectively. Verb properties for novel regulars (*plaw*) and for novel irregulars (*splim*) assume a regularized response (*plawed*, *splimmed*). *T*-tests (for continuous variables) are two-sample, equal variance, except for same-class neighborhood, opposite-class neighborhood, and stem-past changes, where the Satterthwaite approximation (t_s) was used to estimate degrees of freedom due to unequal group variance. Fisher's exact tests are given for categorical variables.

squeeze-squeezed, c.f., *freeze-froze*); 16 novel "consistent regular" verbs (*plaw*), which were primarily expected to elicit regularized responses (*plawed*), and 16 novel "irregular" verbs (*splim*), which were phonologically similar to the stems of real irregular verbs (e.g., *splim* is similar to *swim*), increasing the likelihood that participants produce at least some irregularized responses (*splam*) (Ullman, 1993; Ullman et al., 2005; Walenski et al., 2007). The 32 consistent regulars and 32 irregulars were matched groupwise a priori on stem (unmarked form) and past-tense frequency, phonological structure and verb imageability, and did not differ on several other factors (see Table 3, and *Covariates* section below). The stems of the 16 inconsistent regulars were phonologically similar to the stems of existing irregulars in English (e.g., *squeeze* is similar to *freeze*). The stems of the consistent regulars shared their rimes with the stems of few or no irregulars.

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, 2009; Walenski et al., 2007). Each verb stem was visually presented 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. Participants 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 participant's oral response (via a microphone connected to the computer). Presentation of the next stimulus either was initiated by the experimenter via button press after the participant 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. Participants were given 10 practice items before the task began: 3 regular, 3 irregular, and 4 novel verbs.

2.3. *Response coding*

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 (average transcription reliability was 91% on a randomly spot-checked subset of 5 participants with autism and 5 controls). 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 response-types described just below (Walenski et al., 2007). Note that responses with false starts (where the participant began to respond, paused, then started again) and other minor phonological errors (e.g., pauses, phonemes that were said more loudly or quietly than other phonemes in the word) were considered correct for accuracy analyses, but were excluded for response time analyses.

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 participant (*slip*, *squeeze*). 'Inflection' errors were –*ing*- or –*s* affixed forms of the verb given to the participant (*slipping*, *squeezes*). 'Multiple –*ed*' errors were defined as the exact form of the verb stem given to the participant with two or more additions of the –*ed* affix (*slippeded*, *squeezededed*). Allomorph errors were defined as the exact form of the stem with a phonologically inappropriate form of the –*ed* suffix (e.g., adding syllabic/Id/to squeeze instead of the appropriate/d/) '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*. . .).

For irregular verbs, 'over-regularized' errors consisted of the given stem plus the appropriate allomorph of the –*ed* affix (*bringed*). 'Irregular affix' errors were defined as the omission of a final/t/in an irregular past tense that reduces the vowel and adds a final -t (e.g., *sleep-slep* instead of *slept*). '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 regular and irregular verbs (*plaw*, *splim*), 'regularized' responses were defined as the given stem affixed with the appropriate –*ed* allomorph (*plawed*, *splimmed*). Irregularized responses (*splam*), and all other unexpected responses (e.g., *plawing*, *splammed*), were categorized as for real regular verbs.

2.4. Data analysis

Prior to analysis, one participant with autism (right handed, with both comorbid ADHD and comorbid OCD) was excluded as a performance outlier (7% correct over all real items). Omitting this participant did not change the pattern of significance for group differences of participant characteristics reported in Table 1. For the remaining participants, we compared performance between the autism and control groups at six types of forms: consistent regulars, over-regularization errors to real irregulars, and novel regularizations, as well as real irregulars, inconsistent regulars, and novel irregularizations. The first three types are predicted by dual-system views to be rule-produced, and predicted on a single-system view to depend especially on phonology; the latter three are predicted to depend particularly on the mental lexicon (dual-system) or on semantics (single-system).

For each comparison of interest, first-responses were analyzed using mixed-effects regression models, with crossed random effects of participant and item on the intercept. Accuracy (correct/incorrect) and response time constituted the dependent measures. A logit-link function (for binary outcome data) was used for accuracy analyses (SAS 9.2 proc glimmix). Response times were analyzed with SAS 9.2 proc mixed. The fixed effects were participant group (autism vs. control) and item type for the comparison of consistent regular vs irregular verbs, but just participant group for the other comparisons (inconsistent regulars, regularized and irregularized responses to novel verbs, and over-regularization errors). Fixed effect variables were dummy coded (group: autism = 1, control = 0; item type: irregular = 1, regular = 0). *F*-statistics are reported for main effects and interactions (type III tests). For planned comparisons of group and item-type differences we report the regression coefficient B (with standard error in parentheses), *t*-statistics, and 95% confidence intervals. 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.

For response time analyses of correct first responses, responses that had a false start or other errors that were included in accuracy analyses (see response coding section above) were excluded (2.2% of data), as were response time errors (7.1% of data). Response time (RT) errors were defined as cases where no RT was recorded (i.e., participant did not respond or the response was not loud enough to trigger the timer), or RTs that reflected a noise other than the participant's response (monitored by the experimenter during testing). In addition, two steps were taken in order to reduce the skewness and kurtosis of the distribution of response times: RTs were natural-log transformed, and outliers were removed (0.9% of data). Outliers were defined as any response outside the inner fence of the data distribution, that is, responses more than (1.5 * the interquartile range) above the third quartile, or less than that below the first quartile of the data. The amount of data excluded was roughly equally distributed across the six data sets for each criterion.

2.4.1. Covariates

In order to provide the fairest test of the predictions made by the different hypotheses, and to ensure that systematic differences between participant groups or item types were not due to confounding factors, a number of participant-, task-, and item-level factors were considered for inclusion as covariates in the regression models, as in prior studies (Prado & Ullman, 2009; Walenski et al., 2007). It is not possible to match groups or regular and irregular verbs on all relevant factors. Moreover, determining that groups are matched by means of *t*-tests is likely insufficient to rule out potential confounds due to group differences (Mervis & Klein-Tasman, 2004). Therefore, even though our two participant groups and the regular and irregular items were chosen to be similar (and indeed, differed minimally in important characteristics; see Tables 1 and 3), we nevertheless aimed to reduce variability contributed by individual participants and/or items, and to determine whether any potential group or verb-type differences remain when these variables have been brought under statistical control in our data analyses.

In order to avoid the inclusion of a large number of variables with little or no predictive value in each model, we employed a two-stage process to select the covariates for each analysis. This also enabled us to avoid any a priori assumptions that the same variables should necessarily predict both of our dependent variables (accuracy and response time) for the different items and response types we analyzed. Note that if different covariates are indeed important for different analyses, this will be reflected in the final models. For this two-stage process, we first ran each model with all potential covariates. Second, for each model, we then removed those covariates that did not predict the dependent variable (see below). Results from these final models with these covariates are reported below.

Seven participant-level factors were considered (Table 1): age, years of education (Dabrowska, 2008) (using imputed values based on the child's presumed grade given their age, for 6 of the participants with autism and 5 of the typically developing boys for whom this variable was missing), full scale IQ (FSIQ), verbal IQ, handedness (right vs. non-right), whether the participant had a diagnosis of co-morbid obsessive–compulsive disorder (OCD), and whether the participant had a co-morbid diagnosis of attention-deficit hyperactivity disorder (ADHD). We did not have standard verbal IQ score for one participant with autism; thus, the first stage of covariate selection omitted this participant, who was also omitted in the final models which included this covariate (see below). Note that WIAT-R reading scores were not considered as a covariate because several participants had missing values that could not be reasonably imputed (4 boys with autism and 1 control). Since including this covariate would have removed 20% of the data from the autism group, but only 4% of the data from the control group, its inclusion could have unreasonably skewed our analyses.

Four task-level variables were examined (Prado & Ullman, 2009; Walenski et al., 2007). First, natural-log transformed item-order was examined to account for any variability attributable to the order of verbs in the presentation list (e.g., differences in performance for items at the beginning of the list vs. items at the end of the list, due to practice effects within the task). We also examined three variables that can capture order effects not accounted for by item-order itself. For real verbs, we created a variable coding whether or not the previous verb was of the same inflectional class, i.e., given a value of 1 if both the previous and the current verbs were regular or both irregular, because repeating a similar response or producing a different type of response may affect response time and accuracy. For all verbs, we also created another variable coding whether the previous verb was a regular verb (either consistent or inconsistent) or not (irregular or novel), as perseveration of the regular pattern may influence responses to irregular or novel verbs. Finally, we also coded whether the previous verb was real or novel, because switching between real and novel items could also affect performance.

Twelve item-level factors that potentially also affect production accuracy or response times, many of which are important for examining single-mechanism model predictions, were also considered as covariates (Table 3), as in previous studies (Prado & Ullman, 2009; Walenski et al., 2007).

We examined a binary variable coding whether or not the response began with a fricative phoneme. This variable provides an important control, as initial fricative phonemes may be detected with a delayed latency relative to non-fricative phonemes with computer-recorded response time measurements (Kessler, Treiman, & Mullennix, 2002).

For real words, word frequency may influence production (Alegre & Gordon, 1999; Barry, Morrison, & Ellis, 1997; Dye, Walenski, Prado, Mostofsky, & Ullman, 2013; Marcus et al., 1992; Oldfield & Wingfield, 1965; Prado & Ullman, 2009; Stemberger & MacWhinney, 1986). Frequency counts of the stem and past-tense form were calculated for each real verb as the natural log of the sum of the raw frequencies – plus 1 to avoid $\ln(0)$ – using two English-language counts: (1) the Francis and Kucera count ("FK"; Francis and Kucera, 1982); and (2) a count from 44 million words of unedited Associated Press news wires from between February and December 1988 ("AP"; Church, 1988; Ullman, 1999).

In addition, longer words may require more time for syllabification and articulatory planning (Levelt, Roelofs, & Meyer, 1999; Meyer, Roelofs, & Levelt, 2003), and length may influence past-tense performance (Bird, Lambon Ralph, et al., 2003). Verb stem length was also considered, 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). Both for the stem and the (correct) inflected form, phonological length was computed as the number of phonemes.

We also considered verb imageability for real verbs, as in prior studies (Bird, Howard, & Franklin, 2003; Bird, Lambon Ralph, et al., 2003; Prado & Ullman, 2009), using ratings from 1 (low imageability) to 5 (high imageability) (Prado & Ullman, 2009).

Two phonological neighborhood measures were considered, since phonological similarity is predicted to impact verb production accuracy and/or response time (Prado & Ullman, 2009; Ullman, 1993, 1999; Woollams, Joanisse, & Patterson, 2009). The "phonological neighborhood" of a past-tense form is a function of the type and token frequency of phonologically similar and dissimilar verb forms. 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. Values were computed for novel verbs based on their presumed "expected" past tense forms (i.e., a regular form for novel regular verbs, and most likely irregular form for the novel irregulars).

'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., *ride-rode*) are defined as those irregulars that share the same type of stem-past transformation (e.g., *stride-strode*), 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 the given verb, but have a different stem-past transformation (e.g., *hide-hid*). 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 those 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).

Finally, we examined four additional measures of phonological complexity of the inflected form. The number of consonant phonemes in the coda of the inflected form (e.g., irregular *kept* has two; regular *played* has one) serves as an indication of phonological complexity (Bird, Lambon Ralph, et al., 2003). Second, as evidence suggests that two voiced phonemes within a coda may be less perceptually distinct, we examined whether 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), potentially accounting for differences in performance between regular (always consistently voiced) and irregular (not always consistently voiced) verbs (Bird, Lambon Ralph, et al., 2003). Additionally, as in previous studies (Marcus et al., 1992; Walenski et al., 2007), the number of phonological changes between the stem and past-tense form was computed, since the past tenses of verbs with fewer stem-past changes may be easier to produce. Finally, we coded our items for the 'phonologically irregularity' of their past tense form. As discussed above, it has been claimed that regular morphological forms are phonologically irregular in English (e.g., *beeped* is irregular, *whipped* is not), whereas (many but not all) irregular morphological forms are phonologically regular (Burzio, 2002).

2.4.2. Covariate inclusion

Based on the two-stage process mentioned above, only subsets of these participant-, task- or item-level factors were included in the final regression models (for similar approaches, see Walenski et al., 2007, 2008). After including all covariates in each initial model (stage 1), covariates that did not predict the dependent variable ($p \geq 0.20$) in the model were excluded (stage 2), and the model was then re-run with only the remaining covariates. Importantly, in comparing the results of models with the full set of covariates against those with the reduced set of covariates, for all analyses the models with the reduced set provided a better fit to the data (difference in Bayesian Information Criteria (BIC) > 10; Kass, 1995; Schwarz, 1978): for accuracy analyses, differences in pseudo-BIC (generated for logistic regressions) were greater than 170 in all cases; likewise for response times, the models with the reduced set of covariates also fit better than the models with all covariates (difference in BIC > 14 in all cases). Thus for all analyses we report the results from the models with the reduced set of covariates.

For models with accuracy as the dependent variable, the following covariates were included in the final regression models for real verbs: irregulars vs. consistent regulars (verbal IQ, years of education, item order, fricative onset, stem frequency, same class neighborhood, stem-past changes); inconsistent regulars (years of education, co-morbid OCD); over-regularization errors (same as for the regular vs. irregular contrast). For expected responses to novel verbs, the following covariates warranted inclusion: regularized responses to novel regular verbs (verbal IQ, co-morbid OCD, item order); regularized responses to novel irregular verbs (none); irregularized responses to novel irregular verbs (verbal IQ). For models with response time as the dependent variable, the following covariates warranted inclusion for real verbs: irregulars vs. consistent regulars (handedness, co-morbid OCD, whether the preceding verb was regular or not, opposite class neighborhood); inconsistent regulars (handedness, co-morbid OCD); over-regularization errors (same as for the regular vs irregular contrast). For novel verb response times, the following covariates were included: regularized responses to novel regular verbs (handedness, co-morbid OCD, fricative onset, same class neighborhood, number of inflected-form coda consonants); regularized responses to novel irregular verbs (handedness, co-morbid OCD, item order); irregularized responses to novel irregular verbs (co-morbid OCD).

3. Results

3.1. Past tense production accuracy

The boys with autism did not differ in accuracy from the typically developing control boys on any type of response to any verb type (Table 4). First, there was no difference between the groups at the production of either consistent regulars (*slip-slipped*; $B = 0.25$ (0.41), $t(108) = 0.62$, $p = 0.54$; 95% CI: [−0.56, 1.07]) or irregulars (*sleep-slept*; $B = -0.27$ (0.31), $t(37.6) = 0.87$, $p = 0.39$; 95% CI: [−0.90, 0.36]). Regular accuracy was higher than irregular accuracy both for the boys with autism ($B = -3.02$ (0.48), $t(66) = 6.23$, $p < 0.0001$; 95% CI: [−3.98, −2.05]) and for the controls ($B = -2.49$ (0.46), $t(54.8) = 5.40$, $p < 0.0001$; 95% CI: [−3.42, −1.57]). There was no interaction between participant group (autism/control) and verb type (regular/irregular) ($F(1, 2604) = 2.51$, $p = 0.11$), and no main effect of group ($F(1, 43.6) = 0.00$, $p = 0.98$); as expected, the analysis yielded a significant main effect of verb type (regular more accurate than irregular; $F(1,46.4) = 38.64$, $p < 0.0001$). Second, the two groups also did not differ on inconsistent regulars (*squeeze-squeezed*; $B = -0.11$ (0.37), $t(46.9) = 0.30$, $p = 0.77$; 95% CI: [−0.86, 0.64]), novel regulars (regularized responses: *plaw-plawed*; $B = 0.43$ (0.50), $t(43.6) = 0.85$, $p = 0.40$; 95% CI: [−0.59, 1.44]), or novel irregulars (regularized responses: *splim-splimmed*; $B = -0.37$ (0.36), $t(37.0) = 1.03$, $p = 0.31$; 95% CI: [−1.09, 0.36]; irregularized responses: *splim-splam*; $B = 0.65$ (0.42), $t(35.3) = 1.54$, $p = 0.13$; 95% CI: [−0.21, 1.50]). Finally, over-regularization errors to existing irregular verbs were made at a similar rate by the two groups (*sleep-sleeped*; $B = -0.14$ (0.32), $t(36.2) = 0.45$, $p = 0.66$; 95% CI: [−0.80, 0.51]).

Table 4
Past tense production accuracy.

	Autism ($n = 19$)		TD controls ($n = 25$)		Group differences on adjusted means
	Response rate	Adjusted means	Response rate	Adjusted means	
Consistent regular (*slip*)					
Correct (*slipped*)	95.6% (1.1)	3.85 (0.39)	95.4% (1.5)	3.60 (0.35)	$t(108) = 0.62$, $p = 0.54$
Unmarked (*slip*)	1.0% (0.4)	–	0.9% (0.3)	–	–
Inflection (*slipping*)	0	–	0.3% (0.3)	–	–
Multiple –*ed* (*slippeded*)	0	–	0.2% (0.2)	–	–
Other	3.4% (1.1)	–	1.7% (1.0)	–	–
Irregular (*sleep*)					
Correct (*slept*)	64.3% (5.5)	0.84 (0.33)	68.7% (3.5)	1.11 (0.31)	$t(37.6) = 0.87$, $p = 0.39$
Over-regularized (*sleeped*)	22.6% (4.4)	−1.84 (0.32)	23.3% (2.7)	−1.70 (0.29)	$t(36.2) = 0.45$, $p = 0.66$
Unmarked (*sleep*)	3.2% (0.7)	–	1.6% (0.5)	–	–
Inflection (*sleeping*)	0	–	0.5% (0.4)	–	–
Multiple –*ed* (*sleepeded*)	0.2% (0.2)	–	0	–	–
Over-irregularized (*slape*)	3.0% (0.6)	–	2.0% (0.7)	–	–
Irregular affix (*slep*)	2.0% (0.8)	–	0.4% (0.3)	–	–
Double marked (*slepted*)	0.2% (0.2)	–	0.3% (0.2)	–	–
Other	4.6% (1.1)	–	2.1% (0.9)	–	–
Inconsistent regular (*squeeze*)					
Correct (*squeezed*)	92.1% (1.8)	2.66 (0.32)	92.5% (1.9)	2.78 (0.30)	$t(46.9) = 0.30$, $p = 0.77$
Unmarked (*squeeze*)	2.3% (1.2)	–	2.3% (0.8)	–	–
Inflection (*squeezing*)	0	–	0.8% (0.5)	–	–
Allomorph error (*squeeze –ed*)	0.3% (0.3)	–	0	–	–
Irregularized (*squoze*)	2.6% (0.7)	–	0.8% (0.4)	–	–
Irregular affix (*squez*)	0	–	0.3% (0.3)	–	–
Double marked (*squozed*)	0	–	0.3% (0.3)	–	–
Other	2.6% (1.1)	–	2.3% (0.8)	–	–
Novel regular (*splim*)					
Regularized (*splimmed*)	83.6% (5.0)	2.52 (0.40)	86.7% (3.5)	2.09 (0.33)	$t(43.6) = 0.85$, $p = 0.40$
Irregularized (*splam*)	1.0% (0.5)	–	0.5% (0.3)	–	–
Unmarked (*splim*)	2.0% (1.1)	–	1.8% (0.8)	–	–
Multiple –*ed* (*splimmeded*)	0	–	0.5% (0.5)	–	–
Double marked (*splammed*)	0	–	0.3% (0.3)	–	–
Other	13.5% (4.5)	–	10.3% (3.1)	–	–
Novel irregular (*splim*)					
Regularized (*splimmed*)	60.2% (5.3)	0.51 (0.32)	67.4% (4.4)	0.88 (0.30)	$t(37.0) = 1.03$, $p = 0.31$
Irregularized (*splam*)	20.4% (4.8)	−1.63 (0.34)	13.6% (3.0)	−2.28 (0.31)	$t(35.3) = 1.54$, $p = 0.13$
Unmarked (*splim*)	4.3% (1.2)	–	2.5% (1.1)	–	–
Inflection (*splimming*)	0.7% (0.7)	–	0	–	–
Allomorph error (*splim –ed*)	1.3% (0.6)	–	0	–	–
Double marked (*splammed*)	1.6% (0.6)	–	1.0% (0.5)	–	–
Other	11.5% (2.7)	–	15.5% (3.6)	–	–

Note: Mean percentages for each response type are computed for each subject and then averaged over subjects (response rate, white columns). Standard errors are shown in parentheses. See text for definitions of error types. Percentages may not add up to 100% due to rounding. Because mixed effects logistic regression models may be inaccurate with very small sample sizes, *t*-statistics are given only for comparisons in which the response-type constituted at least 10% of responses in both subject groups (except for 'other' errors for the novel verbs, as this error category does not constitute a homogenous class). See text for full results from each analysis (including regression coefficients and confidence intervals). Adjusted accuracy means (and standard errors) from the logistic regressions are also presented (gray-shaded columns). See text for the covariates contributing to the adjusted means. Note that the adjusted means may be transformed into the probability of that response (which may be thought of as a measure of the likelihood of the response) with the equation $y = 1/(1 + e^{-x})$, where x is the adjusted mean. 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.

3.2. Past tense production response times

Unlike accuracy, response times showed significant group differences – crucially, though, only for certain conditions (Table 5). First of all, the boys with autism had faster response times than control participants for consistent regular past tenses (*slipped*; $B = -0.26$ (0.11), $t(41.3) = 2.28$, $p = 0.03$; 95% CI: [−0.49, −0.03]) but not for irregular past tenses (*slept*; $B = -0.19$ (0.11), $t(43.2) = 1.65$, $p = 0.11$; 95% CI: [−0.42, 0.04]). Moreover, the boys with autism were faster to produce consistent regulars than irregulars ($B = 0.09$ (0.03), $t(156) = 2.76$, $p = 0.007$; 95% CI: [0.03, 0.16]), while the controls showed no such difference ($B = 0.03$ (0.03), $t(102) = 0.82$, $p = 0.42$; 95% CI: [−0.04, 0.09]). The significant speed increase for consistent regulars for the boys with autism was reflected in a significant interaction between verb-type (consistent regular vs. irregular) and participant-group (autism vs. control): $F(1,1935) = 3.77$, $p = 0.05$. Main effects of participant group (boys with autism faster than controls overall; $F(1,40.2) = 3.96$, $p = 0.05$) and verb type (regulars faster than irregulars overall; $F(1,63.2) = 4.82$, $p = 0.03$) were also significant.

Table 5
Past tense production response times.

Response type	Autism ($n = 19$)		TD controls ($n = 25$)		Group differences on adjusted means
	RT means	Adjusted means	RT means	Adjusted means	
Consistent regular (*slipped*)[*]	7.62/2039 ms	7.55 (0.08)	7.77/2368 ms	7.81 (0.07)	$t(41.3) = 2.28$, $p = 0.03$
Irregular (*slept*)	7.71/2231 ms	7.64 (0.09)	7.78/2392 ms	7.83 (0.07)	$t(43.2) = 1.65$, $p = 0.11$
Additional –*ed* affixed forms					
Over-regularized irregular (*bringed*)[*]	7.58/1959 ms	7.52 (0.08)	7.83/2515 ms	7.87 (0.07)	$t(29.3) = 3.24$, $p = 0.003$
Regularized novel regulars (*plawed*)[*]	7.81/2465 ms	7.74 (0.11)	8.00/2981 ms	8.04 (0.09)	$t(38.7) = 2.15$, $p = 0.04$
Regularized novel irregulars (*splimmed*)[*]	7.87/2618 ms	7.76 (0.11)	8.07/3197 ms	8.11 (0.09)	$t(37.5) = 2.45$, $p = 0.02$
Additional forms dependent on memory					
Inconsistent regular (*squeezed*)	7.77/2368 ms	7.71 (0.09)	7.80/2441 ms	7.84 (0.08)	$t(39.8) = 1.05$, $p = 0.30$
Irregularized novel irregulars (*splam*)	8.20/3641 ms	8.14 (0.14)	8.13/3395 ms	8.17 (0.13)	$t(25.5) = 0.12$, $p = 0.90$

Note: White columns show the means of natural-log transformed response times (RT) for participants with autism and typically developing (TD) controls; back-transformed means in milliseconds are also provided in each cell. Gray shaded columns contain the adjusted means from the regression models (with standard error in parentheses).

[*] Significant group difference on the adjusted means ($p < 0.05$).

Second, the boys with autism were faster than controls at producing regularized responses to novel regular verbs (*plawed*; $B = -0.30$ (0.14), $t(38.7) = 2.15$, $p = 0.04$; 95% CI: [−0.58, −0.02]), and regularized responses to novel irregular verbs (*splimmed*; $B = -0.35$ (0.14), $t(37.5) = 2.48$, $p = 0.02$; 95% CI: [−0.64, −0.06]). They were also faster when producing over-regularization errors (*bringed*; $B = -0.35$ (0.11), $t(29.3) = 3.24$, $p = 0.003$; 95% CI: [−0.57, −0.13]). In contrast, responses times to inconsistent regulars (*squeezed*; $B = -0.12$ (0.12), $t(39.8) = 1.05$, $p = 0.30$; 95% CI: [−0.37, 0.12]) and to irregularized responses to novel irregular verbs (*splim-splam*; $B = -0.03$ (0.20), $t(25.5) = 0.12$, $p = 0.90$; 95% CI: [−0.43, 0.38]) were not significantly faster for the boys with autism than for the control boys (Table 5).

4. Discussion

On the past tense production task, the boys with autism responded no more or less accurately in any condition than the typically developing control boys. With respect to response times, the boys with autism were faster than the typically developing control boys when producing past tenses of verbs that are predicted by dual-system views to be rule-produced: consistent regular verbs (*slip-slipped*), regularized past tenses of both novel regular (*plaw-plawed*) and novel irregular (*splim-splimmed*) verbs, and over-regularization errors to irregular verbs (*bring-bringed*). In contrast, boys with autism were not significantly faster than controls when producing the past tenses of verbs predicted on dual-system views to depend on the mental lexicon: irregular (*sleep-slept*) or inconsistent regular verbs (*squeeze-squeezed*), or irregularized past tenses of novel verbs (*splim-splam*).

These results do not appear to be explained by a wide range of potentially confounding participant-, task-, and item-level factors whose influence was statistically addressed in our models. It is also unlikely that overt problems with reading explain the pattern of results, since our participants were not reading-impaired (based on self-report and WIAT-R scores; Table 1); in addition, we statistically controlled for a range of item-level factors that might have led to differential reading difficulty (e.g., phonological neighborhood and complexity, word length, frequency, etc.). As the verbs were presented in sentence contexts, it might also be suggested that group differences in the speed of reading influenced our results, as reading speed was not assessed with our standardized measures. However, if the participants with autism indeed read faster than the control boys, they should have shown a speed increase for all items, not just those that dual-system models predict to be rule-produced. Finally, a speed-accuracy tradeoff also does not seem to account for the results in this study, since the boys with autism were not less accurate than the control boys on any condition for which they were faster.

We considered the ability of different theoretical perspectives of language to explain our results. As discussed in Section 1, single-mechanism models of morphology may be able to explain differences between regular and irregular past tenses, within or between groups, to the extent that regulars are more phonologically complex (Bird, Lambon Ralph, et al., 2003; Burzio, 2002; Joanisse & Seidenberg, 1999; McClelland & Patterson, 2002a). However, it is unlikely that this can account for our results. Most importantly, the regular and irregular verbs were matched with respect to multiple phonological properties, both directly (Table 3) and statistically via consideration as covariates. Thus, no differences between regulars and irregulars should be predicted by such models, contrary to our response time findings for the children with autism. Additionally, it is not clear how a phonological advantage for autism (if indeed one were present) might lead to a response time advantage only for regulars, as compared to typically developing children, in particular once phonological complexity is controlled for. Rather, one might expect a speed advantage for all forms, that is, both regulars and irregulars. Note also that even though some aspects of phonologically related functions may be enhanced in autism (Järvinen-Pasley et al., 2008; Norbury et al., 2010), we know of no evidence suggesting faster phonological processing. Finally, we point out that we did not include all possible phonological measures as covariates, and so the regular and irregular verb forms might still have differed phonologically in some respect; thus we cannot definitely rule out this hypothesis.

In contrast, dual-system models of language (Pinker, 1999; Pinker & Ullman, 2002b; Ullman, 2001, 2004; Ullman et al., 1997), together with the Procedural Deficit Hypothesis (Mostofsky et al., 2000; Ullman, 2004; Walenski et al., 2006), offer what we feel is a more likely explanation for the results. Response times were significantly speeded in autism relative to controls in exactly those cases where the grammatical/procedural system is expected to be engaged in –*ed*-affixation: consistent regular past tenses (*slipped*), regularized novel past tenses (*plawed*, *splimmed*), and over-regularization errors (*bringed*). In contrast, no significant speeding of response times was found for forms whose processing is expected to depend on lexical/declarative memory: irregular past tenses (*brought*), inconsistent regular past tenses (*squeezed*), and irregularized novel past tenses (*splam*). There are several ways in which this speeded response time pattern for suffixed forms might reflect an abnormal grammatical/procedural system.

One possibility is that speeded response times to regulars by children with autism reflect difficulty shifting away from the regular pattern in English, as a form of perseveration or repetitive behavior, since the majority of English verbs, and the majority of verbs in our task, take the regular pattern (add –*ed* to the stem). Indeed, repetitive behaviors have been linked to the basal ganglia in autism (Estes et al., 2011; Hollander et al., 2005; Pina-Camacho et al., 2012; Sears et al., 1999). Such basal ganglia-based repetitive behaviors are consistent with the Procedural Deficit Hypothesis, which posits that various functions associated with the basal ganglia (not just procedural memory itself) may be problematic in autism. However, difficulty shifting away from regulars should lead to excess affixation, resulting in, for example, an increased rate of over-regularization errors (e.g., *bringed*) to real irregulars in autism, as well as a greater proportion of regularized responses to novel verbs – contrary to our findings. In addition, due to the difficulty shifting away from the regular pattern, we might expect to see slowed response times for the production of real and novel irregular responses, even if no accuracy differences are found. Again, this is contrary to our results. Therefore our finding of speeded response times for regulars is unlikely to reflect a difficulty shifting away from the regular pattern.

A second possibility is that learning in procedural memory is enhanced in boys with autism relative to typically developing boys. Enhanced learning might lead to stronger memory traces and/or more efficient processing, yielding the speeded response time pattern we observed. However, while there are some suggestions in the literature that procedural memory is spared in autism (Barnes et al., 2008; Boucher, Mayes, & Bigham, 2008), we are not aware of any independent evidence of *enhanced* procedural learning in autism. Nonetheless, this remains a possible explanation that requires additional exploration.

Third, an indirect effect that could lead to a speeded procedural system is a reduction in inhibition (‘‘blocking’’) from lexical/declarative memory to the grammatical/procedural system during the computation of –*ed*-affixed forms. With less inhibition than normal, the computation of forms dependent on the procedural system may speed up, leading to faster-than-normal response times. This altered interaction could be caused by a reduction in connectivity between the two systems, a possibility that is potentially consistent with hypotheses that autism reflects reduced connectivity or cortical synchronization between multiple brain regions (Herbert, 2005; Herbert et al., 2004; Just, Cherkassky, Keller, Kana, & Minshew, 2007; Just et al., 2004; but see Keown et al., 2013; Supekar et al., 2013). However, if the efficacy of blocking were reduced (for any reason), we would expect to see an increase in regularized responses to novel irregular verbs and in over-regularization errors to real irregular verbs, relative to controls, as these forms would not be blocked by memory-dependent irregulars. Contrary to these predictions, neither type of form was produced at a rate different than that of controls (Table 4).

Fourth, children with autism may have difficulties with procedural memory, but may compensate by memorizing regulars in lexical memory (which appears to be generally spared, and may even be enhanced in some respects; see Section 1), and using stored exemplars to generalize the regular pattern to novel forms and over-regularizations (Alegre & Gordon, 1999; Hartshorne & Ullman, 2006; Pinker, 1999; Prado & Ullman, 2009; Ullman & Pierpont, 2005; van der Lely & Ullman, 2001). If this were the case, the prevalence of the regular pattern in memory in children with autism might lead to faster memory-dependent responses for –*ed*-affixed forms than for irregular forms; note that this might also be expected by single-mechanism models, in which regulars and irregulars both depend on associative memory. However, in this case, one would expect to see interference from phonologically similar items in memory that do not take the regular pattern. That is, inconsistent regulars and over-regularization errors to existing irregular verbs should both show interference from irregulars, and thus should pattern together (with neither showing speeded production), since the stems of both are similar to the stems of irregular verbs. This was not observed, suggesting that a reliance on lexical/associative memory for both regulars and irregulars seems unlikely to explain the current results.

Instead, it seems to us more plausible that there may be a similar basal ganglia-based abnormality in autism as in Tourette syndrome, in particular one that affects the processing of already-learned grammatical/procedural skills. Frontal/basal-ganglia abnormalities are claimed to underlie disinhibited behaviors in Tourette syndrome (Mink, 2001; Swerdlow & Young, 2001). This disinhibition appears to extend to the processing of procedural knowledge, manifested by speeded processing, including in the production of regularly affixed forms (but not lexically dependent forms) (Walenski et al., 2007). The speeded response times in autism observed here closely mirror these findings in children with Tourette syndrome (Walenski et al., 2007), implicating similar disinhibition in the speeded responses in autism. It is not clear why such disinhibited or unsuppressed procedural processing should lead only to speeded affixation and not also to over-affixation, that is, increased error rates of forms such as *walkeded* and *bringed*. Children with Tourette syndrome show a slightly increased production of such forms (Walenski et al., 2007), whereas in the present study the children with autism did not show signs of such a pattern. One possibility is that the basal ganglia abnormalities are more severe or more reliably found in Tourette syndrome, impacting error rates as well as response times. Note that unsuppressed procedural processing is not expected to lead to slower response times for irregulars (unlike the hypothesis that the children with autism are perseverating on the regular pattern; see above), a prediction that is consistent with the findings.

In addition, both autism and Tourette syndrome are strongly associated with unsuppressed motor activity, such as motor (and vocal) tics and stereotypies (repetitive movements or behaviors) (Ringman & Jankovic, 2000). Functional and structural neuroimaging studies of these behaviors have implicated the basal ganglia in autism (Estes et al., 2011; Hollander et al., 2005; Pina-Camacho et al., 2012; Sears et al., 1999), as well as in Tourette syndrome (Mink, 2001; Swerdlow & Young, 2001). Moreover, co-morbidity between autism and tic disorders, including Tourette syndrome, appears to be fairly common (Baron-Cohen, Mortimore, Moriarty, Izzaguirre, & Robertson, 1999; Baron-Cohen, Scahill, Izaguirre, Hornsey, & Robertson, 1999; Canitano & Vivanti, 2007; Gjevik, Eldevik, Fjæran-Granum, & Sponheim, 2011; Lugnegård, Hallerbäck, & Gillberg, 2011; Mattila et al., 2010; but see Memari, Ziaee, Mirfazeli, & Kordi, 2012; Ringman & Jankovic, 2000; Stern & Robertson, 1997). Note that while none of the children in our study met diagnostic criteria for (co-morbid) Tourette syndrome, we did not examine our participants for milder tic behaviors, nor did we have an independent measure of frontal or basal-ganglia size, shape, or function in our participants. Overall, the evidence seems to suggest that Tourette-like disinhibition of grammatical/procedural processing may provide a plausible account for our current findings.

In contrast to the abnormal production of regular affixed forms, the production of lexically dependent forms such as irregulars, inconsistent regulars, and novel irregularizations appeared to be typical with respect both to accuracy and to response times. This is consistent with prior findings of relatively strong lexical and semantic memory in (high-functioning) autism (Ben Shalom, 2003; Boucher et al., 2008; Crane & Goddard, 2008; Minshew & Goldstein, 2001; Ullman, 2004; Walenski et al., 2006). Note that although a previous study found atypically fast response times for the processing of lexical items (Walenski et al., 2008), these results were obtained with a different task (picture naming), and only for low frequency items, whose frequencies were in fact lower than those of the lexically dependent past-tense forms in the present study.

Thus the patterns both for –*ed* suffixed forms and lexically dependent forms appear to be consistent with the predictions of dual-system models of morphology and the Procedural Deficit Hypothesis of autism. The response time pattern, which was similar to that seen previously in Tourette syndrome, suggests frontal/basal-ganglia disinhibition that affects the computation of morphologically complex –*ed*-affixed forms in high-functioning autism, with sparing of lexically dependent forms. The pattern of typical accuracy is consistent with the high verbal IQ of our participants, as well as with several prior studies of syntax and morphology in high-functioning individuals with autism.

Because the initial predictions of the Procedural Deficit Hypothesis were fairly broad (including the possibility of less accurate or slowed response times for –*ed* suffixed forms), it might be thought that any outcome would be compatible with this perspective. However, this is not the case. Rather, the hypothesis specifically predicts particular abnormalities in the computation of –*ed*-suffixed forms, with relative sparing of the computation of lexically dependent forms in individuals with high-functioning autism. There are several alternative outcomes that would have gainsaid our predictions, including typical computation of both –*ed* suffixed and lexically dependent forms, atypical computation of both types of forms, abnormal computation of only lexically dependent forms, and random patterns of group differences among –*ed*-suffixed or lexically-dependent forms (e.g., some –*ed*-suffixed forms speeded and others either not speeded or even slowed, relative to controls). We therefore suggest that the consistent, specific pattern that we observed is indeed compatible with the Procedural Deficit Hypothesis.

Finally, the results also suggest that even when children with autism match their typically developing peers in response accuracy, such that their language appears normal (e.g., on diagnostic instruments), the processes and/or brain structures underlying such apparently typical language may yet be atypical in the disorder. It remains to be seen whether the profile of a fast procedural system indicated by the current results could underlie abnormal (and perhaps enhanced) performance in other aspects of language (e.g., syntax or even pragmatics) or cognition in autism.

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