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Impaired artificial grammar learning in agrammatism

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ABSTRACT

It is often assumed that language is supported by domain-specific neural mechanisms, in part based on neuropsychological data from aphasia. If, however, language relies on domain-general mechanisms, it would be expected that deficits in non-linguistic cognitive processing should co-occur with aphasia. In this paper, we report a study of sequential learning by agrammatic aphasic patients and control participants matched for age, socio-economic status and non-verbal intelligence. Participants were first exposed to strings derived from an artificial grammar after which they were asked to classify a set of new strings, some of which were generated by the same grammar whereas others were not. Although both groups of participants performed well in the training phase of the experiment, only the control participants were able to classify novel test items better than chance. The results show that breakdown of language in agrammatic aphasia is associated with an impairment in artificial grammar learning, indicating damage to domain-general neural mechanisms subserving both language and sequential learning.

1. Introduction

For more than a quarter of a century, cognitive scientists have debated whether higher-order cognitive processes are subserved by separate, domain-specific brain mechanisms or whether the same neural substrate may support several cognitive functions in a domain-general fashion (e.g., Barrett & Kurzban, 2006; Elman et al., 1996; Fodor, 1983; Newcombe, Ratliff, Shallcross, & Twyman, 2009; Prinz, 2006). This modularity debate has played out particularly strongly in the study of language, where the proponents of the influential Chomskyan approach have long held that the cognitive and neural machinery employed in acquiring and processing language is uniquely dedicated to this purpose (e.g., Chomsky, 1965; Grodzinsky & Santi, 2008; Pinker, 1991). However, a growing bulk of work from psycholinguistics (e.g., Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Kamide, Altmann, & Haywood, 2003—see Farmer, Misyak, & Christiansen, in press) and neuroimaging (e.g., Heiser, Iacoboni, Maeda, Marcus, & Mazziotta, 2003; January, Trueswell, & Thompson-Schill, 2009—see Müller, 2009, for a review) has begun to question the putative domain-specificity of language. Indeed, there may be no viable evolutionary account of a domain-specific language mechanism (at least for arbitrary aspects of language; Chater, Reali, & Christiansen, 2009; Smith & Kirby, 2008). Instead, it has been hypothesized that pre-existing neural mechanisms have been recruited to support language while still retaining their original function (Christiansen & Chater, 2008), similarly to the proposed cultural recycling of prior cortical maps for recent human innovations such as reading and arithmetic (Dehaene & Cohen, 2007). This hypothesis predicts that even classically defined “language areas” in the perisylvian region of the human brain are not specific to

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language but, rather, are subserving broader, domain-general mental functions.

Of the putative language regions, Broca's area (Brodmann areas 44/45) is perhaps the most canonical one. It is uncontroversial that this part of the left inferior frontal gyrus plays a crucial role in language. Since Broca's (1861) original analysis of his patient Leborgne's language impairment, the brain region that bears his name has been associated with the production of language. This conception of Broca's area was further underscored by his contemporaries, Wernicke (1874) and Lichtheim (1885), and subsequently popularized by Geschwind (1965) as part of the now classic Wernicke–Lichtheim–Geschwind model of brain-language function (see Poeppel & Hickok, 2004, for a review). More recent work has emphasized the role of Broca's area in language syntax, in part based on neuropsychological data from aphasic patients with damage to this region of the brain and diagnosed with agrammatic aphasia (e.g., Goodglass & Kaplan, 1983). Although fMRI data suggest that both phonological and lexical processing may activate the left inferior frontal region (e.g., Sahin, Pinker, Cash, Schomer, & Halgren, 2009; see Heim, 2005, for a review), it has been argued that Broca's region subserves only a narrow, syntax-specific function associated with movement (Grodzinsky, 2000; Grodzinsky & Santi, 2008).

The purported language-specificity of Broca's area has, however, long been disputed, starting with Hughlings-Jackson's (1878-79/2006) non-modular account of language. Although the language-specific notion of Broca's area ended up dominating subsequent theorizing, it has been suggested more recently that the deficit associated with damage to this brain region may be broader in nature relating to behavioral (Grossman, 1980) or motor sequencing (Kimura & Archibald, 1974). The domain-general perspective on the left inferior frontal gyrus is now receiving support from a growing number of neuroimaging studies showing that this part of cortex is involved in a number of non-linguistic functions, including (a) gesture recognition (Villarreal et al., 2008), (b) arm movements (Schlaug, Knorr, & Seitz, 1994), (c) mental imagery of hand grasping movements (Decety et al., 1994; Grafton, Arbib, Fadiga, and Rizzolatti, 1996), (d) preparation and execution of target-directed actions (particularly grasping) (Binkofski et al., 1999; Grèzes, Armony, Rowe, & Passingham, 2003; Krams, Buccino, Rushworth, & Deiber, 1998), (e) tasks involving mental rotation of the hand (Parsons et al., 1995), (f) attempted use of the paralyzed hand by patients who have recovered from subcortical infarctions (Chollet et al., 1991), (g) sequence processing (Gelfand & Bookheimer, 2003), (h) maintenance of rules (Bunge et al., 2005), (i) visual and auditory perception of action (Johnson-Frey et al., 2003) (j) imitative tasks (Heiser, Iacoboni, Maeda, Marcus, and Mazziotta, 2003), (k) representations of mouth articulation gestures (Demonet et al., 1992), (l) hierarchically organized human behavior (Koechlin & Jubault, 2006), and (m) music processing (Maess, Koelsch, Gunter, & Friederici, 2001; Molnar-Szakacs & Overy, 2006).

A property common to most of the non-linguistic tasks that elicit activation in Broca's area is the processing and production of perceptual, cognitive or action sequences. Indeed, as originally suggested by Kimura and Archibald (1974) and Grossman (1980), there is an obvious connection between language and sequential learning and processing: both involve the encoding and subsequent processing of discrete elements found in a sequence. Not surprisingly, this type of learning has become an important experimental paradigm for studying language acquisition and processing (sometimes under the guise of 'artificial language learning', Gómez & Gerken, 2000, 'statistical learning', Saffran, 2003, or 'artificial grammar learning', Perruchet & Pacton, 2006). Although the growing bulk of work on such sequential learning is motivated by theoretical questions concerning language acquisition, the empirical relationship between the two in terms of underlying mechanisms is much less clear. Similarly, evidence for the domain-general nature of Broca's area and its role in language is also indirect, relying on comparisons of neural activation patterns elicited across separate series of studies and populations that are administered either linguistic or non-linguistic tasks. Here, we investigate whether the left inferior frontal region plays a functional role in domain-general sequential learning. Specifically, we employ an artificial grammar learning (AGL, Reber, 1967) task to test the prediction that breakdown of language in agrammatic aphasia should be associated with impaired AGL performance. This is not a trivial prediction given that AGL performance is generally considered "to remain robust in the face of time, lack of attentional resources and psychological disorder" (Cleeremans, Destrebecqz, & Boyer, 1998, p. 407—see also Reber, 1993). Next, we first briefly discuss current approaches to AGL and agrammatic aphasia as relevant to the present paper, before describing and reporting the results of our AGL experiment testing sequential learning in agrammatism.

1.1. Current approaches to artificial grammar learning

Since Reber's (1967) pioneering work, AGL has been one of the main paradigms for studying the learning of sequentially ordered information. In a typical AGL study, participants are first exposed to a set of strings, derived from an artificial grammar, under the pretext of a memory or pattern learning experiment. Participants are then told of the rule-based nature of the strings and asked to classify a new set of strings—some of which are generated by the same grammar and some of which are not—according to whether these novel strings follow the same rules as the ones they saw earlier. Classification performance on such AGL tasks is typically above chance, despite participants' general lack of overt knowledge of the underlying regularities.

This kind of sequential learning has been demonstrated across a variety of domains, including visual processing (Fiser & Aslin, 2002a), detecting orthographic regularities of written words (Pacton, Perruchet, Fayol, & Cleeremans, 2001), visuomotor learning (Hunt & Aslin, 2001), tactile sequence learning (Conway & Christiansen, 2005), and non-linguistic, auditory processing (Saffran, Johnson, Aslin, & Newport, 1999). AGL-style tasks have also been successfully employed across a variety of language learning situations, including speech segmentation (Curtin, Mintz, & Christiansen, 2005; Saffran, Aslin, & Newport, 1996;

Saffran, Newport, & Aslin, 1996), discovering complex word-internal structure between nonadjacent elements (Newport & Aslin, 2004; Onnis, Monaghan, Richmond, & Chater, 2005; Peña, Bonnatti, Nespor, & Mehler, 2002), acquiring gender-like morphological systems (Brooks, Braine, Catalano, Brody, & Sudhalter, 1993; Frigo & McDonald, 1998), locating syntactic phrase boundaries (Saffran, 2002), using function words to delineate phrases (Green, 1979), integrating prosodic and morphological cues in the learning of phrase structure (Morgan, Meier, & Newport, 1987), integrating phonological and distributional cues (Monaghan, Chater, & Christiansen, 2005), and detecting long-distance relationships between words (Gómez, 2002; Onnis, Christiansen, Chater, & Gómez, 2003).

Evidence of language-related sequential learning has been found with as little as 2 min of exposure (Saffran, Aslin, et al., 1996) and when learners are not explicitly focused on learning the structure of the linguistic stimuli (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). More generally, sequential learning has been shown to be fast, robust, and automatic in nature (e.g., Cleeremans & McClelland, 1991; Curran & Keele, 1993; Stadler, 1992) and present across development from infancy to adulthood to old age (e.g., Fiser & Aslin, 2002a; Fiser & Aslin, 2002b; Howard & Howard, 1992; Kirkham, Slemmer, & Johnson, 2002; Meulemans, Van der Linden, & Perruchet, 1998; Saffran, Aslin, et al., 1996; Saffran, Newport, et al., 1996). However, considerable individual differences in implicit learning do exist, and tend to be associated with differences in language ability (Misyak & Christiansen, in press; Misyak, Christiansen, & Tomblin, 2010). For example, consistent differences in learning have been observed between children and adults (Saffran, 2002), and appear to correlate with verbal ability in older adults (as well as educational attainment and occupational status; Cherry & Stadler, 1995). Additionally, dyslexia has been associated with poor learning on a serial reaction-time (SRT) task (Howard, Howard, Japikse, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003; Vicari et al., 2005—but see also Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Münte, 2006; Waber et al., 2003, for conflicting evidence), while both language/learning disabilities (Plante, Gómez, & Gerken, 2002) and specific language impairment (Evans, Saffran, & Robe-Torres, 2009; Hsu, Christiansen, Tomblin, Zhang, & Gómez, 2006) have been shown to affect AGL performance negatively. Together, these results point to an overlap in mechanisms for language and sequential learning as predicted by recent language evolution theory (Christiansen & Chater, 2008; see also Christiansen & Ellefson, 2002; Dominey, Hoen, Blanc, & Lelekov-Boissard, 2003; Ullman, 2004).

1.2. Current approaches to agrammatic aphasia

If the same domain-general mechanisms are involved in both language and sequential learning, we would expect that severe language impairment as evidenced in agrammatic aphasia should also be associated with a deficit in AGL. Stable agrammatic aphasics thus constitute an important clinical population for testing the hypothesized overlap in neural substrate for language and artificial grammar learning. Prior to the onset of aphasia, people with acquired agrammatism have undergone normal grammatical development and have functioned with normal grammatical competence. They have then typically sustained a lesion to the left frontal lobe often involving Broca's area, although there is evidence that injury in Brodmann areas 44/45 may not be necessary and sufficient to produce the relevant behaviors (see, e.g., Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004; Kaan & Swaab, 2002).

By definition, agrammatic aphasics have disproportionate difficulty in syntactic processing and/or producing or interpreting bound and free functor morphemes (Goodglass, 1993; Goodglass & Kaplan, 1983—see Martin, 2006; Novick, Trueswell, & Thompson-Schill, 2005, for recent reviews). Their language production is characteristically halting and effortful, with free and bound functors (e.g., *the*, *and*, *but*, *-ed*, *-ing*) either omitted or substituted, and complex or non-canonical constructions not attempted (Goodglass, 1976; Menn & Obler, 1990). This production-based definition of agrammatic aphasia has been seen as having a comprehension-based counterpart by researchers seeking an underlying cause that is less domain-specific. Although spoken simple sentences may be understood when they do not contain constituents that might potentially be semantically interchangeable, comprehension is typically impaired, particularly for complex or non-canonical sentences, (e.g., Caramazza & Zurif, 1976; De Bleser, 1987; Schwartz, Saffran, & Marin, 1980), although Berndt, Mitchum, and Haendiges (1996) report a meta-study in which aphasics defined in production terms were found to be heterogeneous in comprehending passive structures. Further, Linebarger, Schwartz, and Saffran (1983) have shown that there may be gradations in the impairment of comprehension, with grammaticality judgments surviving (see also Devescovi et al., 1997; but cf. Zurif & Grodzinsky, 1983).

Researchers have sought to understand agrammatic aphasia in terms of theories of normal syntactic processing. Building on theoretical constructs from formal linguistics, syntactic processing has been conceived as involving structure building (creating constituents such as noun phrases), checking agreement between inflections, mapping thematic roles onto positions in the sentence, and dealing with the complexity created by non-canonical ordering of such roles. Theories of agrammatic aphasia differ in terms of which parts of the competence-level description of language processing are considered to be impaired; as in the Trace Deletion Hypothesis (see, e.g., Grodzinsky, 1995), thematic roles (Schwartz et al., 1980), and noun/verb differences (Fillenbaum, Jones, & Wepman, 1961; Myerson & Goodglass, 1972; although see Berndt, Haendiges, & Wozniak, 1997). In general, there is an ongoing attempt to map formal linguistic theorizing onto language processing (see, e.g., Grodzinsky & Friederici, 2006), and an attempt to establish the primacy and temporal priority of syntactic processing in normal language performance (see, e.g., Friederici, 2002).

Against this trend is the view that syntactic processing and syntactic categories are not prior in development (e.g., Tomasello, 2000) and only constitute one component in a richly interactive system in which syntactic competence participates along with more general, less language specific and less modality specific cognitive competences (see, e.g., Gibson & Pearlmutter, 1998; Hickok, Bellugi, & Klima, 1998; Hoen et al., 2003; MacDonald & Christiansen, 2001). On these accounts, damage to Broca's area is thought to lead to more general cognitive deficits that in turn are reflected in impaired language performance—e.g., by disrupting cognitive control processes (Novick et al., 2005) or domain-general associative processing (Dick et al., 2001) involved in language comprehension—and in which impairments may be compensated by the rich informational redundancy present in language (see, e.g., Shillcock & Hackett, 1998).

Past research on agrammatic aphasia drawing on a variety of disciplines has thus produced a mixed picture, both in terms of behavioral characterizations and their explanations (see also, Martin, 2006). We suggest that one means of understanding the data from agrammatic aphasia is to look at the pattern of survival and loss of simpler processes that may plausibly subserve language processing. One such process is the implicit learning of sequential information: both language and sequential learning involve the extraction and further processing of discrete elements occurring in complex sequences.

Prior work on sequence learning suggests that agrammatic aphasics might be able to perform a visually-based implicit learning task. Using an SRT task, Goschke, Friederici, Kotz, and van Kampen (2001) found that Broca's aphasics were able to learn visually presented spatio-motor sequences but were impaired on learning phoneme sequences—even though both had the same underlying structure, 12343214, for which anticipation of upcoming elements requires learning of second-order probabilities. Dominey et al. (2003) replicated the positive visuo-spatial learning outcome for agrammatic aphasic participants in an SRT task using the slightly simpler sequence structure 123213. Unlike healthy controls, the agrammatic aphasic patients were unable to generalize the 123213 structure to new instances (with different surface forms) under explicit SRT performance conditions. However, this result is not necessarily indicative of impaired implicit learning in agrammatic aphasia: neuroimaging results have pointed to different neural systems being involved in implicit and explicit SRT performance (e.g., Rüsseler, Hennighausen, Münte, & Rösler, 2003), suggesting that the agrammatics' failure to generalize under explicit SRT conditions may be unrelated to their learning abilities under implicit SRT conditions. In a related experiment, Hoen et al. (2003) employed an analogy-like task in which participants were instructed to study a set of letter strings instantiating the structure 123213 (e.g., HBSBHS and YPBPYB) so that they could complete the sequence KBT_ _ _. As in the Dominey et al. (2003) study, the agrammatic participants were not able to make explicit generalizations to new sequences with the same underlying 123213 structure based on what they had learned in the analogy task. With extensive training, their performance improved not only on the explicit sequence task but also on natural language sentences with a similar structure. Together, these studies suggest that visually mediated sequence learning under largely implicit learning conditions may be spared in agrammatism, whereas performance under more explicit conditions may be impaired[1]. This interpretation is consistent with the pattern of selective deficits to explicit learning relative to implicit learning in other clinical populations (e.g., Abrams & Reber, 1988). In contrast, we predicted that the inability to process natural language syntax in agrammatism would be reflected in a failure to learn the implicit structure of artificial grammars.

2. Method

2.1. Participants

We tested seven participants (mean age = 68) diagnosed as having agrammatic aphasia by experienced clinicians from the NHS trusts in Edinburgh, Scotland, based on presentation of an array of clinical behaviors (see Table 1). Agrammatism was differentially diagnosed from conduction aphasia primarily by the presence of non-fluent output based on extensive clinical observation (Goodglass, 1992), performance on the BDAE Cookie Theft picture description task (Goodglass & Kaplan, 1983), evidence of auditory comprehension deficits from either PALPA (Kay, Lesser, & Coltheart, 1992) or WAB (Kertesz, 1982), and in the case of V.C., CT scan information on the location of cerebral damage. For four of the participants, scores on lexical level tasks from PALPA and WAB indicated that proceeding with the TROG (Bishop, 1989) assessment of receptive grammar would not be possible due to the lexical processing difficulties evidenced. Details of the TROG assessments for the three participants who underwent this test are given in Appendix A. All aphasic participants had suffered a left hemisphere insult and were a minimum of 9 months post-onset. Seven age-matched control participants with no history of dyslexia, cognitive or psychiatric problems, stroke or head-injury were also recruited (mean age = 64; $t(12) = 0.70$, $p = 0.49$), and additionally matched with the aphasic participants for sex and socio-economic background. None of the fourteen participants had participated in implicit learning studies previously.

To ensure that aphasic and control participants were equated on non-verbal intelligence, they were administered Raven's Progressive Matrices (Raven, 1962). These tests are considered representative measures of analytic intelligence, requiring abstract reasoning to complete the task of matching complete patterns and understanding relationships between discrete figures and spatially related wholes. The version employed here—the Coloured Progres-

[1] Instead of an implicit versus explicit learning issue, Dominey and colleagues (Dominey et al., 2003; Hoen et al., 2003) see it as a surface regularity versus abstract structure difference, with only the healthy controls being able to extract the latter from the former. However, as noted by Redington and Chater (1996), such transfer effects do not require that the participants have extracted any abstract structure during learning; rather, abstraction may be more parsimoniously explained as simply being performed at test. Given the explicit nature of the abstraction task used in these studies, it is likely to be harder to do for agrammatic aphasics than control participants, thus potentially explaining the discrepancy between agrammatic performance in the implicit and explicit conditions. Indeed, Dominey et al. (2003) found that the severity of the aphasic syntactic deficit was positively correlated with performance on the explicit abstract structure task.

Table 1
Individual histories of the aphasic participants.

Patient	Age	Sex	Post-onset (months)	Lesion details	Diagnostic indicator of agrammatism				
					Non-fluent speech	Prohibitive lexical difficulties on[a]		BDAE cookie theft	TROG
						PALPA	WAB		
V.C.	69	F	30	Left CVH	+	–	n/a	n/a	+
F.B.	83	F	72	Left CVA, Broca's area	+	–	n/a	n/a	+
G.C.	76	M	15	Left CVA, Broca's area	+	+	+	n/a	n/a
A.R.	67	F	12	Left CVA, Broca's area	+	+	n/a	+	n/a
D.H.	56	M	13	Left CVA, fronto-temporal	+	+	n/a	n/a	n/a
M.G.	71	F	15	Left CVA, Broca's area	+	+	n/a	+	n/a
C.B.	53	M	9	Left CVA	+	–	n/a	n/a	+

Note. F = female; M = male; CVH = cerebroventricular haemorrhage; CVA = cerebral vascular accident; PALPA = psycholinguistic assessments of language processing in aphasia (spoken word picture matching subtest; diagnostic criterion for agrammatism: 2/40 incorrect); WAB = western aphasia battery (verbal comprehension; G.C. failed to complete more than the first six items); BDAE = Boston diagnostic aphasia exam; TROG = test for the reception of grammar (diagnostic criterion for agrammatism: 6/20 incorrect); + = indicated agrammatism; – = did not indicate agrammatism; n/a = failed to take or complete this test.

[a] Lexical difficulties on PALPA or WAB prohibited further investigation of grammatical processing.

sive Matrices: Sets A, A_B and B—is designed for children, older subjects, or those suffering from cognitive and verbal disabilities (maximum score = 36). All participants were tested individually in a quiet location after they had completed the implicit learning task, and care was taken to ensure that they understood the task instructions.

There was no difference in the Raven's Coloured Progressive Matrices scores between the control group (mean = 28.8) and the agrammatic group (mean = 28.8). Successful completion of this test reflects competence in perceptual processing (perceiving figures, encoding them in terms of component parts and determining correspondences between them; Hunt, 1974) and the requisite associated working memory skills (Carpenter, Just, & Shell, 1990). Additionally, the lack of difference between group performances shows that the agrammatic group is able to follow experimental task instructions of similar complexity to those used for the AGL task. Thus, the two groups are well matched on this measure of non-verbal perceptual and cognitive skills as well as on their ability to follow instructions in an experimental task.

2.2. Materials

Forty unique grammatical strings consisting of 3–6 characters were generated using the finite-state grammar devised by Reber and Allen (1978) (see Fig. 1). Easily distinguishable symbols from the Zapf dingbats font (point-size 18) were used instead of the traditional letter elements to ensure that the agrammatic participants' performance would not be affected by any potential reading deficits that they might have. Twenty of the grammatical strings were used in the training phase and twenty were used in the test phase. Nineteen[2] ungrammatical test strings were generated by introducing violations at one, two, or three places in the grammatical string, resulting in either illegal subsequences of elements or removal of initial or final elements (see Appendix B).

Previous research has indicated that participants' classifications of test items can be affected by how familiar they seem given the training items, with familiarity measured in terms of chunk information or exemplar similarity (see e.g., Conway & Christiansen, 2005; Pothos & Bailey, 2000, for reviews). Thus, associative chunk strength (ACS) measures the average frequency with which the chunks in a test item—i.e., its component pairs and triples of elements—occur in the training items (Knowlton & Squire, 1994). Anchor strength (AS) is calculated as the relative frequency of the initial and final chunks in similar positions in the training items (Knowlton & Squire, 1994). Chunk novelty (CN) is the number of chunks that did not appear in any training item, whether they form legal or illegal element sequences (Redington & Chater, 1996). Novel chunk position (NCP) is measured as the number of chunks that occur in novel absolute positions where they did not occur during training (Johnstone & Shanks, 1999). Finally, global similarity (GS) is the number of elements by which a test item differs from its nearest match in the training set (Vokey & Brooks, 1992). Each of these measures of familiarity has been shown to affect classification performance, independent of whether a particular item is grammatical or not. For example, an ungrammatical test item that has high ACS, AS or GS will seem more familiar to participants, and therefore be likely to be judged as grammatical, and likewise if it has low CN or NCP. On the other hand, a grammatical item with low ACS, AS or GS will appear somewhat unfamiliar and may consequently be classified as ungrammatical, and similarly when it has high CN or NCP. We therefore ensured that grammatical and ungrammatical items did not differ in ACS ($t < 1$), AS ($t(37) = 1.17$, $p = .25$), NCP ($t < 1$), GS ($t(37) = 1.45$, $p = .16$), and length ($t < 1$), though CN was lower for grammatical items (mean = 1.0) compared to ungrammatical items (mean = 2.2; $t(37) = 2.81$, $p < .01$).[3]

[2] Originally, there were 20 ungrammatical test items but due to a programming error one item (❂●■) was repeated. We removed all data points for the second occurrence of this item from further analyses. None of the results differs significantly if the data from the repeated item are included.

[3] Originally, a secondary goal of this study was to determine whether participants might be able to use CN to differentiate between grammatical and ungrammatical test items. Hence, we allowed CN to be lower for grammatical items compared to ungrammatical items, with the expectation that low-CN items would appear more familiar to participants because they contain few unseen chunks. However, as this manipulation did not affect group differences, we therefore folded the discussion of CN into the treatment of other familiarity variables.

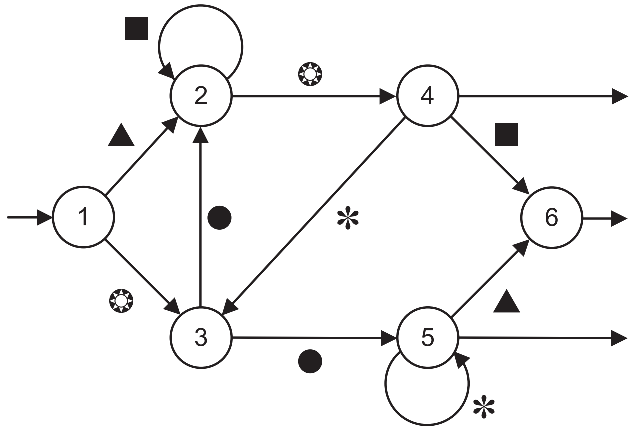

Fig. 1. The artificial (finite-state) grammar used to generate the grammatical strings for the experiment by starting at node 1 and then following the arrows to other nodes, each time writing out the symbol associated with a specific arrow. For example, the item ▲■✪■ is produced by going from node 1 to node 2, then looping back to node 2, followed by visits to nodes 4 and 6.

2.3. Procedure

Participants were told they were taking part in a pattern recognition experiment and started out doing a match–mismatch training task without feedback (Conway & Christiansen, 2005). The advantage of such a cover task is that it focuses participants' attention on the stimuli without explicitly singling out test relevant information. Moreover, focusing attention in this manner has been shown to improve incidental learning of the underlying regularities of visual stimuli (Turk-Browne, Junge, & Scholl, 2005), and thus should facilitate learning across participant groups in our AGL task.

On each training trial, participants first saw one grammatical string for 7 s, followed by a 3-s gap, and a second grammatical string for 7 s. Participants were asked to use a button box to indicate whether they judged the second string to match the first. This training method requires no verbal responses and demands that the participants attend to the first item closely in order to carry out the task successfully. Training was split into two sessions to minimize the effect of fatigue on the older subjects. Forty randomized pairs of grammatical items were presented in each session; 20 were matching, 20 were non-matching.

After training, participants were instructed that the previously seen strings had been generated by a complex set of rules specifying which symbols can follow which; and that they would now be presented with a new set of strings, some of which would follow the same rules as before while others would not. They were encouraged to use their "gut feeling" to decide which was which. Participants then classified 20 grammatical and 19 ungrammatical strings randomly intermixed.

All training and test materials were presented on an Apple PowerBook 140 laptop computer using the PsyScope presentation software (Cohen, MacWhinney, Flatt, & Provost, 1993) and responses recorded using a button box (New Micros, Inc., Dallas, TX). Both training and test instructions were read aloud by the experimenter while the participant read along on the computer screen. The experimenter then queried the participant to ensure that the instructions had been completely understood and answered any questions the participant might have about the procedure before commencing the training/test tasks.

3. Results

Both participant groups performed well on the match–mismatch AGL training task, with the control group scoring 96% correct and the aphasic group 91% correct. Although this difference approaches significance ($t(12) = 2.05$, $p = .07$), additional analyses indicated that there was no correlation between training and test scores, neither across ($R^2 = .06$, $F(1, 12) = .79$, $p = .39$) nor within groups (agrammatics: $R^2 = .0007$, $F(1, 5) = .003$, $p = .96$; controls: $R^2 = .05$, $F(1, 5) = .24$, $p = .65$). Thus, the trend towards a marginal group difference in training performance is unlikely to have contributed to any differences observed in test performance. Moreover, the high agrammatic performance on the training task indicates that they were able to understand the instructions and were engaged in the task.

Results for the test phase of the AGL experiment revealed that the control group was able to classify 63% of the test items correctly, whereas the performance of the aphasic group, with only 51% correct, was significantly lower ($t(12) = 2.53$, $p < .03$). Single-group t-tests indicated that the control participants performed significantly better than chance ($t(6) = 3.2$, $p < .02$), whereas the aphasic participants did not ($t < 1$). Additional analyses showed that the performance difference between the two groups was due to the control participants correctly endorsing more grammatical items (65%) than the aphasic participants (39%; $t(12) = 2.37$, $p < .04$). There was no difference between the correct rejection of ungrammatical items by the control group (56%) and the aphasic group (58%; $t < 1$). Thus, the control participants accepted significantly more grammatical items correctly (i.e., classifying them as following the same rules as the training items) but were no better than the agrammatic aphasics at rejecting ungrammatical items (i.e., classifying them as not following the same rules as the training stimuli). We cannot fully resolve this difference between correct rejections and correct endorsements in the current paper but see it as a potentially important subject for future research.

To investigate whether participants used familiarity information to facilitate classification performance, we conducted a correlation analysis with the familiarity measures as independent variables and endorsement rate as the dependent measure (i.e., the average probability across participants of endorsing an item as grammatical). Table 2 shows that only the grammaticality of the test strings appears to have affected classification performance, with grammaticality being associated with higher endorsement rates. We also found several additional intercorrelations between the familiarity variables. CN correlates significantly with grammaticality and there was a positive correlation between CN and NCP, both of which tended to have high values associated with low ACS. NCP was additionally negatively correlated with AS, which, in turn, is likely to have high values associated with high values of ACS. When

Table 2
Intercorrelations between familiarity variables calculated across all participants.

Statistic	Endorsement	Grammaticality	ACS	AS	CN	NCP	GS
Grammaticality	.52***						
ACS	.03	.03					
AS	.27	.19	.63***				
CN	−.22	−.42**	−.53**	−.25			
NCP	−.14	−.05	−.53**	−.59***	.59***		
GS	−.05	.23	−.30	−.51**	.14	.78***	
Length	−.18	−.02	.17	.10	.18	.44**	.35*

Note. ACS = associative chunk strength; AS = anchor strength; CN = chunk novelty; NCP = novel chunk position; GS = global similarity.
* $p < .05$.
** $p < .01$.
*** $p < .001$ (two-tailed, $n = 39$ test strings).

Table 3
Regression coefficients from analyses of aphasic and control participants.

Participants	Gram.	ACS	AS	CN	NCP	GS	Length
Aphasic	−.0355	−.0244	.0462†	−.0404	.0397	−.0309	−.0185
Control	.2153*	−.0125	.0597	−.0303	.0414	−.0501	−.0683

Note. Gram. = grammaticality; ACS = associative chunk strength; AS = anchor strength; CN = chunk novelty; NCP = novel chunk position; GS = global similarity.
* $p < .05$.
† $p < .06$.

GS is high (indicating dissimilarity from training items), AS tends to be low whereas NCP is likely to be high. Finally, the length of test stimuli was positively correlated with both NCP and GS, indicating that the longer a test item is the more likely it is to have chunks in novel positions and to be dissimilar from training items.

We additionally conducted two multiple regression analyses to determine which of the familiarity variables best predicted endorsement rate: one for each of the two experimental groups because they differed in their classification performance. Using the familiarity variables to predict item endorsement rate, the regression analysis for the aphasic group was not significant ($R^2 = .17$, $F(7, 1) < 1$). As indicated by Table 3, none of the individual predictors were significant when controlling for the other variables though AS was a marginally significant predictor of aphasic endorsement rates. In contrast, the regression for the control group was significant ($R^2 = .36$, $F(7, 1) = 2.54$, $p < .05$) with grammaticality as the only significant independent predictor of control endorsement rates. Rather than using surface-based information, it appears that the control group used knowledge of the underlying structure of the training items (grammaticality) to achieve their above-chance classification performance. By comparison, the aphasic participants may have been misled, at least in part, by information about the beginnings and ends of strings (AS).

4. Discussion

In this study, we administered an AGL task to agrammatic aphasic and control participants, matched for age, social-economic status, and non-verbal intelligence. Although both groups performed well on the match–mismatch training task, only the control participants were able to perform above chance during the test phase. Crucially, because of the identical performance on the Raven's Coloured Progressive Matrices tests, the differences in AGL performance cannot be attributed to the agrammatic group having poor visual–perceptual skills (Hunt, 1974), low visuo-spatial working memory abilities (Carpenter et al.,1990), or general difficulties participating in an experimental task. Moreover, our correlation and regression analyses indicate that it was not the case that the control participants were simply better at detecting surface aspects of the stimuli because only grammaticality was a significant predictor of classification performance. Given that agrammatic aphasics furthermore have been reported to be able to perform grammaticality judgments for natural language stimuli (e.g., Devescovi et al., 1997; Linebarger et al., 1983), it seems unlikely that their poor AGL performance is due to the metalinguistic nature of the test task. Thus, the results show that breakdown of language in agrammatic aphasia is associated with an impairment in implicit learning—at least as measured by a standard visual AGL task—indicating that the deficit goes beyond language.

Although our analyses indicated that the control participants did not use surface-based information when endorsing test items as grammatical or ungrammatical, this does not necessarily entail that they had acquired the abstract rules of the grammar. Instead, participants might have weighted the different types of surface information differentially for each test item or combined them in a non-linear fashion. Another possibility is that the controls were sensitive to another type of surface information not included in our item analyses. These possibilities seem particularly pertinent when considering that grammaticality on its own only accounts for 27% of the variance in endorsement rates for the test stimuli ($R^2 = .27$, $F(1, 7) = 13.37$, $p < .001$). Moreover, if the participants had acquired the grammar rules, one would expect better performance than the observed 63% correct. Even supposing that participants may have abstracted the relevant rules but are limited in their ability to apply this knowledge to the test items, it seems reasonable to assume that such knowledge should be applied equally to grammatical and ungrammatical items. However, the control group was no better than the agrammatic aphasics at rejecting ungrammatical items. Thus, abstract rule knowledge is unlikely to explain the pattern of performance evinced by the control participants (at least not in isolation; see e.g., Pothos, 2007).

The studies by Goschke et al. (2001) and Dominey et al. (2003) have provided evidence of implicit learning of surface regularities by agrammatic aphasics in visually-based SRT tasks. These two studies differ from the current one in at least two crucial ways that may help explain the discrepancy between their results and ours. Firstly, the SRT paradigm involves some components of learning that differ from those involved in AGL tasks. For example, visuo-spatial SRT learning is unlikely to be purely perceptual or cognitive in nature but also involves regularities represented in terms of motor-based response locations (e.g., Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000). Secondly, the rule-like nature of the regularities in an AGL task is arguably more closely related to those found in natural language than the simple surface regularities of a typical SRT study. The grammar used in our study (illustrated in Fig. 1) has a more complex and locally ambiguous structure than the sequences used in Goschke et al. (2001) and Dominey et al. (2003). Thus, although SRT and AGL tasks are likely to involve partially overlapping neural mechanisms for sequential learning (Forkstam & Petersson, 2005), the AGL paradigm may tap more directly into the kind of implicit learning affected by agrammatic aphasia.

More generally, the association between language breakdown and AGL deficit in agrammatic aphasia argues against strict modularist perspectives on language, in which the mechanisms supporting our syntactic abilities are hypothesized to be dedicated to linguistic processing only (e.g., Grodzinsky, 2000). Instead, our findings support the view that language has evolved to rely on domain-general mechanisms (e.g., Christiansen & Chater, 2008), suggesting that neural damage in agrammatism gives rise to cognitive deficits—including sequential learning impairments—that, in turn, cause the more manifest language problems typically associated with this type of aphasia (e.g., Dick et al., 2001; Dominey et al., 2003; MacDonald & Christiansen, 2001; Novick et al., 2005). This perspective on agrammatic aphasia is further corroborated by recent results showing that Broca's aphasics also have impaired processing of structural relations in musical sequences (Patel, Iversen, Wassenaar, & Hagoort, 2008). Additional evidence for a common domain-general neural substrate for sequential learning and language comes from fMRI studies with normal populations showing that sequence violations in an AGL task—similar to the one used here—activates Broca's area (Petersson, Forkstam, & Ingvar, 2004). Moreover, diffusion tensor magnetic resonance imaging (DTI) data suggest that white matter integrity in Broca's areas predicts success in an AGL task, with higher degrees of integrity resulting in better learning (Floeel, De Vries, Scholz, Breitenstein, & Johansen-Berg, 2009). Underscoring the functional role of Broca's area in sequential learning observed here, studies applying transcranial direct current stimulation (tDCS) during training (De Vries, Barth, Knecht, Zwitserlood, & Floeel, in press) or repetitive transcranial magnetic stimulation (rTMS) during testing (Uddén et al., 2008) have found that AGL performance is positively affected by such stimulation to Brodmann Areas 44/45. These studies in combination with our results indicate that there is considerable overlap in the neural mechanisms involved in language and AGL, and that the impairment evident in agrammatic aphasia does not only affect language but is broader in nature, resulting in a general breakdown of sequential learning and processing.

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Appendix A

Table A: Areas of grammatical processing affected by participants attempting the TROG.

Section of TROG	Participants		
	VC	FB	CB
Nouns	+	+	+
Verbs	+	+	+
Adj	–	–	+
2 Element combinations	+	+	+
Negatives	–	+	+
3 Element combinations	+	+	+
Singular vs. plural pronouns	–	+	+
Reversible actives	–	–	–
Masc. vs. fem pers prons	–	+	+
Sgl v. pl noun inflections	–	–	–
Comparative absolute	–	–	–
Reversible passives	–	–	–
Prepositions in/on	–	–	–
Postmodified subjects	–	–	–
'X but not Y' constructions	–	–	–
Above/below	–	+	+
'Not only X but also Y' constructions	Not completed	+	+
Relative clauses	Not completed	–	–
'Neither X nor Y' constructions	Not completed	–	–
Embedded sentences	Not completed	–	–

Note. + = indicated agrammatism; – = did not indicate agrammatism.

Appendix B. Training stimuli

Training Stimuli

Matched Training Pairs		Unmatched Training Pairs	
❂●■❂■	❂●■❂■	❂●■❂■	▲■■■❂
❂●■■■❂	❂●■■■❂	❂●■■■❂	❂●❂■
▲■■❂■	▲■■❂■	▲■■❂■	▲■■■■❂
▲■■■■❂	▲■■■■❂	▲■■■■❂	❂●■■❂
❂●■❂	❂●■❂	❂●■❂	▲■■■❂■
▲■■■❂■	▲■■■❂■	▲■■■❂■	❂●❂✻●✻
▲■■❂	▲■■❂	▲■■❂	❂●■■■❂
▲■■■❂	▲■■■❂	▲■■■❂	▲■❂✻●❂
▲■❂	▲■❂	▲■❂	▲■■❂
▲■❂✻●❂	▲■❂✻●❂	▲■❂✻●❂	❂●✻
❂●✻▲	❂●✻▲	❂●✻▲	▲■❂
▲■❂✻●✻	▲■❂✻●✻	▲■❂✻●✻	❂●■❂
❂●✻✻▲	❂●✻✻▲	❂●✻✻▲	❂●✻✻✻✻
❂●❂✻●✻	❂●❂✻●✻	❂●❂✻●✻	❂●✻▲
❂●■■❂	❂●■■❂	❂●■■❂	▲■■❂■
▲■❂✻●▲	▲■❂✻●▲	▲■❂✻●▲	❂●✻✻▲
❂●❂■	❂●❂■	❂●❂■	▲■❂✻●✻
❂●✻✻✻	❂●✻✻✻	❂●✻✻✻	❂●■❂■
❂●✻	❂●✻	❂●✻	❂●✻✻✻
❂●✻✻✻✻	❂●✻✻✻✻	❂●✻✻✻✻	▲■❂✻●▲

Appendix C. Test stimuli

Test Stimuli

Grammatical	Ungrammatical
❂●❂	❂●■
❂●▲	❂❂❂
❂●✻✻	❂✻✻✻
❂●❂✻●	●✻✻✻✻
❂●❂✻●❂	●❂✻●❂❂
❂●✻✻✻▲	❂✻✻✻▲
❂●■❂✻●	●■❂✻●
❂●■■❂■	❂❂■■❂
▲❂■	❂●■ [a]
▲❂✻●	▲✻❂
▲■❂■	▲■■▲
▲■❂✻●	▲■■❂❂
▲❂✻●✻	▲■❂✻✻❂
▲❂✻●❂	▲■■✻●✻
▲❂✻●▲	▲❂❂●■❂
▲❂✻●✻▲	▲❂■●❂■
▲❂✻●✻✻	●✻✻✻✻✻
▲❂✻●■❂	■■■■❂❂
▲❂✻●❂■	▲■■✻❂■
▲■■❂✻●	▲■■■✻●

[a] This item was repeated due to a programming error.

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