Title

A case of "order insensitivity"? Natural and artificial language processing in a man with primary progressive aphasia.

Vitor C. Zimmerer & Rosemary A. Varley
University College London

Corresponding author:
Vitor Zimmerer
v.zimmerer@ucl.ac.uk

Abstract

Processing of linear word order (linear configuration) is important for virtually all languages and essential to languages such as English which have little functional morphology. Damage to systems underpinning configurational processing may specifically affect word-order reliant sentence structures. We explore order processing in WR, a man with primary progressive aphasia. In a previous report, we showed how WR showed impaired processing of actives, which rely strongly on word order, but not passives where functional morphology signals thematic roles. Using the artificial grammar learning (AGL) paradigm, we examined WR's ability to process order in non-verbal, visual sequences and compared his profile to that of healthy controls, and aphasic participants with and without severe syntactic disorder. Results suggested that WR, like some other patients with severe syntactic impairment, was unable to detect linear configurational structure. The data are consistent with the notion that disruption of possibly domain-general linearization systems differentially affects processing of active and passive sentence structures. Further research is needed to test this account, and we suggest hypotheses for future studies.

Keywords: Syntax; word order; configuration; primary progressive aphasia; artificial grammar learning

Introduction

In natural language, words occur one after another in a “linear” fashion, and processing of linear constituent order, as one aspect of configuration, is mandatory for successful production and comprehension. English, because of its limited inflectional system, relies heavily on linear configuration. *The lion kills the man* and *The man kills the lion* refer to very different events despite having the exact same lexical items. It has been argued that linearization processes are not specific to language (Boeckx, Martinez-Alvarez, & Leivada, 2014). The ability to process auditory and visual sequences, even when stimuli are meaningless, has been linked to the ability to process language under noise conditions (Conway, Bauernschmidt, Huang, & Pisoni, 2010; Conway, Karpicke, & Pisoni, 2007; Conway & Pisoni, 2008). Furthermore, sequence learning in a serial reaction time task correlated with children’s ability to maintain syntactic structure in a priming task (Kidd, 2012). A meta-analysis of eight studies, collectively examining 186 people with specific language impairment and 203 controls, found that pathological groups were poorer at statistical sequence learning (Lum, Conti-Ramsden, Morgan, & Ullman, 2014).

Impaired linear processing has also been found in acquired syntactic disorders such as aphasia. Artificial grammar learning (AGL) experiments have shown that people with impaired sentence production and comprehension have difficulties processing regularities in sequence order even when stimuli are non-verbal and/or visual. Dominey, Hoen, Blanc and Lelekov-Boissard (2003) tested seven aphasic participants and found that their ability to learn simple and complex artificial grammars respectively predicted their ability to comprehend simple and complex sentences. Christiansen, Kelly, Shillcock, & Greenfield (2010) compared seven aphasic participants with seven controls matched for age and non-verbal intelligence and found that the former performed poorer in AGL. Zimmerer, Cowell, & Varley (2014) investigated AGL in four people with severe aphasia and syntactic disorder, five people with aphasia in absence of syntactic disorder, and ten older controls and found learning profiles in patients with syntactic disorder which did not occur in the other samples. Together, these studies indicate that differences between syntactically impaired and unimpaired participants were not the result of experimental procedures, non-verbal intellectual capacity or general effects of brain damage, but were related to the syntactic impairment itself. However, reports of AGL performance in relation to processing of specific sentence structures are rare. Hoen et al. (2003) explored the effects of a training task involving sequence order manipulation on sentence comprehension in six aphasic participants. They reported improvement only for sentences which were assumed to involve a similar order transformation.

We explore the relationship between general linearization and configurational processing in language. In a previous report in *Cortex*, we described the comprehension ability of WR, a man with primary progressive aphasia (PPA) (Zimmerer, Dąbrowska, Romanowski, Blank, & Varley, 2014). He displayed a striking and rarely reported syntactic profile: In sentence-picture matching tasks, his performance on active transitives (*The man pushes the elephant*) and truncated actives with an auxiliary (*The man is pushing*) was at chance. His performance on full passives (*The elephant is pushed by the man*) as well as on truncated passives (*The man is pushed*) was near ceiling. WR had severe sentence production problems. His spoken output was markedly impoverished. In rare instances of sentence-like output in spontaneous speech he strung together content words connected by *is a* (e.g., *Mary is a holiday is a Turkey*). In spontaneous writing he produced only a small number of sentences, most of which were in the passive voice (e.g., *Can it be used for treatment?*; *As research was Vitor created*). Naming ability on the PALPA54 subtest (Kay, Lesser, & Coltheart, 1992) indicated residual lexical capacity with scores of 59/60 for spoken (with no penalty for phonemic paraphasias as long as the target was recognizable) and 59/60 for written naming.

WR's comprehension profile showed a dissociation which is the reverse of the predominantly reported pattern of good performance on actives and poor performance on passives, and poses a substantial challenge to conventional explanations for syntactic disorder (Druks & Marshall, 1995, 1996). English passives are “harder” with regard to a number of variables (Caplan & Waters, 1999; Drai & Grodzinsky, 2006; Druks, 2002; Grodzinsky, 2000; Mauner, Fromkin, & Cornell, 1993) as they contain more words, more functional morphemes, have a non-canonical word order and, in some theories, involve a transformation from canonical order (or “movement” of constituents) .

However, functional morphemes in passives contain strong cues for interpretation. The verb phrase morphology (be+TNS V+PastP, e.g., *is pushed*), which in child development first emerges as the state passive (e.g., *it's broken*), appears to be grounded in stative use and biased towards assigning its subject an inactive role (Brooks & Tomasello, 1999; Israel, Johnson, & Brooks, 2001; Riches, 2013). On the other hand, the prepositional phrase by + NP (e.g., *by the elephant*) is a strong cue for agency. It is used in passives or agentive nominalizations (e.g., *performances by the whole team*) in an estimated 70% of instances (see Zimmerer, Dąbrowska, Romanowski, Blank, & Varley, 2014, for corpus-based results). Zimmerer et al. (2014) demonstrated that WR used both verb and prepositional phrase morphology in isolation or together in order to assign agent/patient roles. Active sentences, and in particular those used for testing WR's syntactic comprehension, lack cues of this type. Functional morphology, if present, was not reliable as a cue for determining semantic roles. For instance, the NP in *NP be+TNS V+ing* can have many roles such as agent (*The man is* *pushing the elephant*), patient (*The dress is selling*), experiencer (*The woman is watching the game*) or instrument (*The computer is enabling her to speak*). Interpretation of English actives relies more on word order. All active sentences used in testing WR's comprehension could have been interpreted correctly using the common bias that the agent appears first (Ferreira, 2003).

WR's profile presented a valuable opportunity to investigate linear order processing and its relationship to configurational processing in language, and specifically, the issue of whether the difficulties with comprehension of actives may be associated with a more general impairment of linear structure processing. We hypothesized that WR would display impaired AGL behavior when processing linear configurational information in non-verbal sequences.

Artificial grammar learning and the grammar A^nB^n

AGL (Reber, 1967) is a commonly employed paradigm that tests processing of sequence structure. In a training phase, participants are exposed to sequences of (nonsense) stimuli. Each sequence is unique but all are generated by a common set of rules. In the test phase, new sequences are presented. Some are generated by the same grammar, others violate it. The participant accepts or rejects each sequence based on its "fit" to the training set. Acceptance/rejection patterns provide insight into which structural properties of the artificial grammar were learned spontaneously and generalized to the new sequences. AGL tasks engage neural language areas, in particular left inferior frontal regions (Bahlmann, Schubotz, & Friederici, 2008; Bahlmann, Schubotz, Mueller, Koester, & Friederici, 2009; Petersson, Folia, & Hagoort, 2012; Petersson, Forkstam, & Ingvar, 2004).

For the current study AGL sequences were generated by the grammar A^nB^n. In A^nB^n sequences, a number of stimuli classified as *A* are followed by the same number of stimuli classified as *B* (e.g., *AABB*, *AAABBB*, *AAAABBBB*). A^nB^n sequences have linear configurational properties: All stimuli of one class precede the stimuli of the other class, and the first class is *A*. A^nB^n sequences also contain non-configurational properties: The numbers of stimuli from each class match. There is strong evidence, including from self-reports after the experiment, that participants who learn non-configurational properties do so by counting and comparing the number of stimuli of each class, and participants without syntactic disorder more consistently attend to configurational (order) than non-configurational (counting) structure (de Vries, Monaghan, Knecht, & Zwitserlood, 2008; Hochmann, Azadpour, & Mehler, 2008; Perruchet & Rey, 2005; Zimmerer, Cowell, & Varley, 2011; Zimmerer, Cowell, et al., 2014). Some non-impaired individuals learn the configurational structure only, but none learn only non-configurational structures. Performances are similar across auditory and visual modalities (Zimmerer, Cowell et al., 2011).[1]

Zimmerer, Cowell et al. (2014) investigated A^nB^n learning in four people with severe aphasia and syntactic disorder, five aphasic controls without syntactic disorder, and ten older healthy controls. Two syntactically-impaired participants, SA and SO, displayed atypical behavior. They learned the non-configurational properties (counting) without learning the configurational properties (order), i.e., they rejected sequences like *AABBB*, but accepted sequences like *BBBAAA* and *AABABB*. We concluded that they were insensitive to linear configuration in the experiment as the rejection of non-configurational violations only requires tracking of the number of item occurrences, but not of any structure beyond that. Both SA and SO had large left perisylvian lesions and severely impaired processing of both active and passive sentences, and therefore results gave little insight into the relationship between linear configurational impairment in AGL and the ability to process specific sentence structures.

Experiment

Participant

WR was 62 years old at the time of the experiment. Four years previously, he was diagnosed with logopenic PPA (Gorno-Tempini et al., 2011). Non-language cognition was unimpaired during the course of the investigation reported here. His Performance IQ (Wechsler, 1999) was 119. Structural MR scanning revealed bilateral atrophy to fronto-temporal perisylvian regions (Fig. 1), which was greatest in the left superior temporal gyrus. With disease progression, he displayed a decline in auditory comprehension. In the third year post-diagnosis and consistent with bilateral temporal lobe atrophy, WR was diagnosed with cortical deafness. Although his performance in auditory comprehension tasks was at or near chance, written word comprehension was only mildly impaired and remained stable over time. Written sentence comprehension and production displayed more gradual decline (Table 1), consistent with Thompson et al.'s (2013) observation that some people with logopenic PPA become syntactically impaired over time, and an unusual comprehension pattern emerged (chance level performance on actives, ceiling performance on passives (Table 2)).

Figure 1. Structural MR images of WR's brain in coronal and sagittal (left) views, showing fronto-temporal perisylvian atrophy.

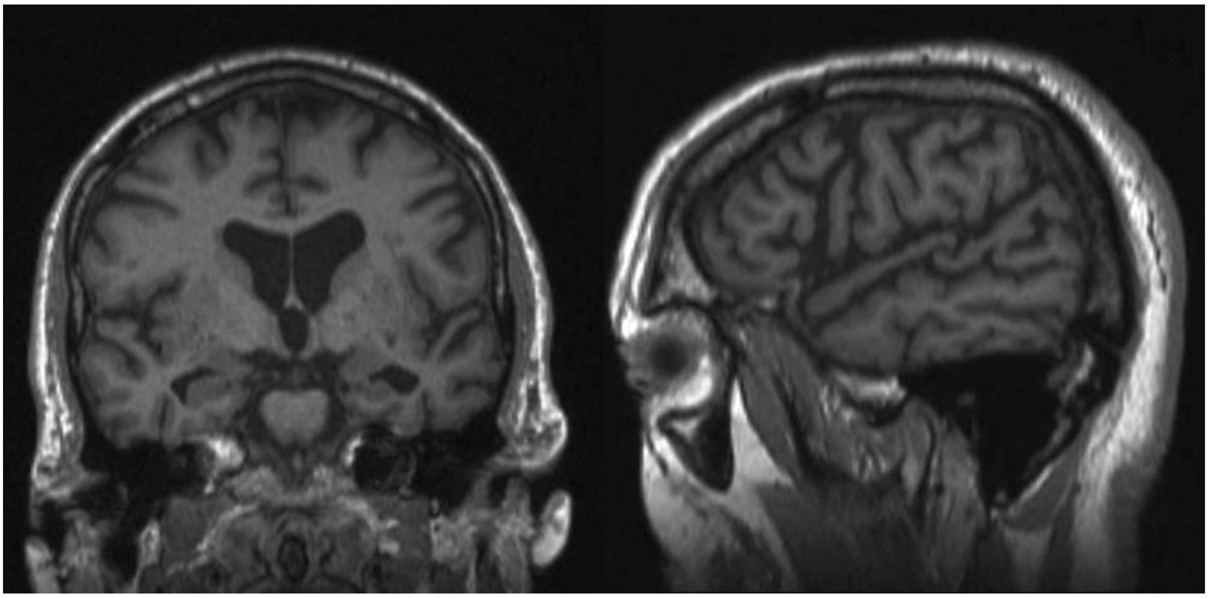


Table 1. WR's performance on written and spoken tests of lexical and grammatical processing in years 1, 2 and 3 post-diagnosis (years 2.5, 3.5 and 4.5 post symptom onset). Chance level is 25% for word-picture matching tasks and 50% for all other tasks.

Test	**Year 1**	**Year 2**	**Year 3**
Spoken minimal pairs	80%	73%	65%
Spoken lexical decision	74%	70%	60%
Spoken word-picture matching	100%	98%	69%
Spoken synonym judgments	90%	84%	58%
Written lexical decision	98%	99%	98%
Written word-picture matching	100%	100%	100%
Written synonym judgment	97%	98%	96%
Spoken sentence-picture matching	98%	93%	65%
Written sentence-picture matching	81%	78%	52%

Table 2. Results of three sentence-picture matching tasks reported in Zimmerer, Cowell et al. (2014). Tests involved selection from a choice of two pictures. Asterisks denote significant (p<.05) deviations from chance performance (50% accuracy).

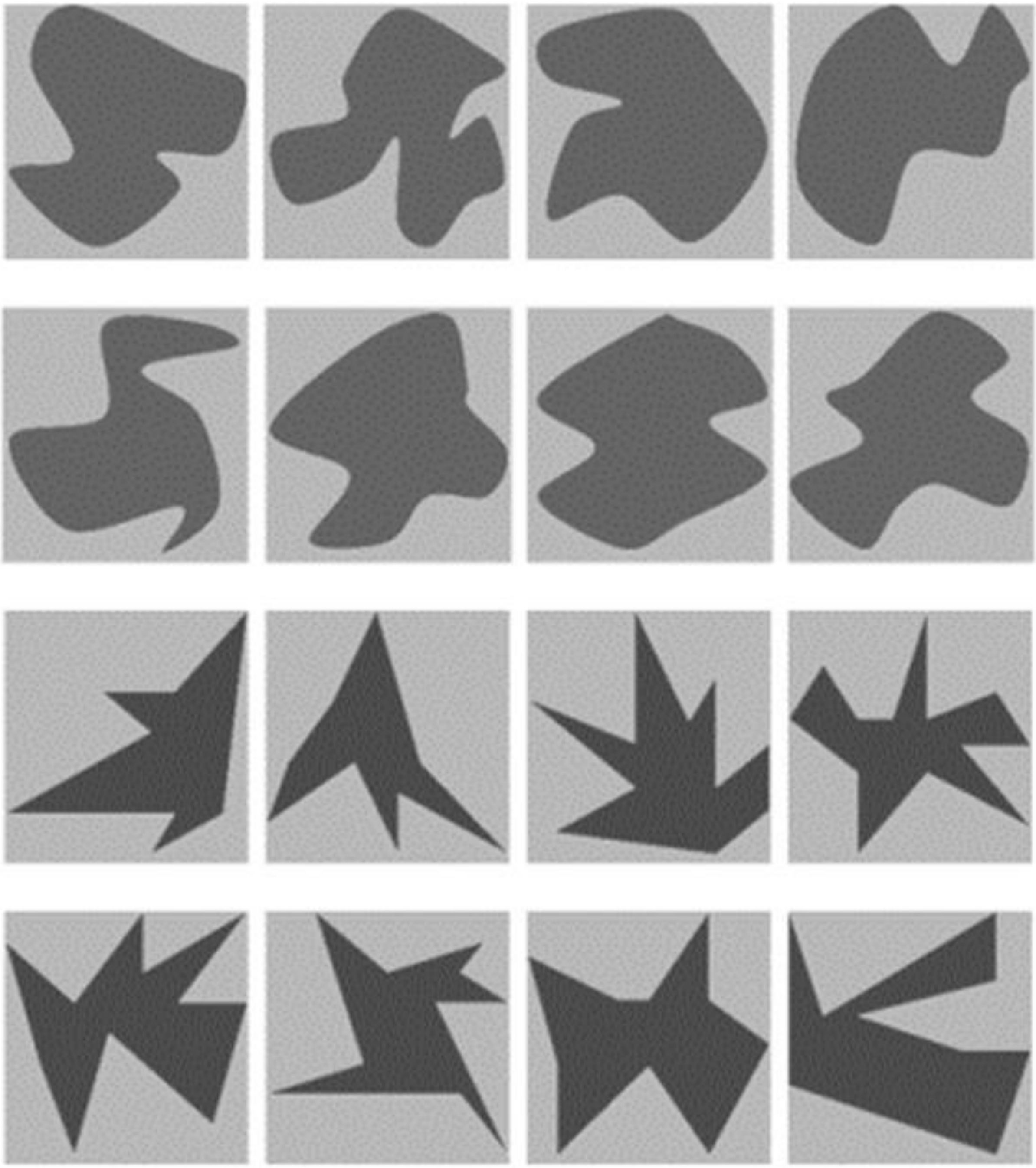
Sentence type		Example(s)	N. of correct responses (% accuracy)
Exp. 1	Reversible active transitives	*The man pushes the elephant.*	18/50 (36%)
	Reversible full passive	*The man is pushed by the elephant*.	47/50 (94%*)
Exp. 2	Irreversible active transitives with spatial by-phrase	*The man by the woman shoots the rabbit.* *The man shoots the rabbit by the woman.*	1/60 (2%*)
	Irreversible transitive actives	*The man shoots the rabbit.*	30/30 (100%*)
	Irreversible full passives	*The rabbit is shot by the man*.	30/30 (100%*)
Exp. 3	Truncated actives	*The man is pushing*.	17/36 (47%)
	Truncated passives	*The man is pushed*.	31/36 (86%*)

Methods

We used the same methods as Zimmerer, Cowell et al. (2011, 2014) to allow comparability with control and aphasic data reported therein (see online supplement for full Methods description). WR was tested in the visual modality, which is consistent with prior AGL research conducted on people with aphasia. WR participated in the AGL experiment two months after the reversible sentence comprehension test took place. He gave informed consent to participation. Ethical approval was granted by the local NHS Research Ethics Committee (08/H1308/32).

WR was trained on 72 A^nB^n sequences (e.g., *AAABBB*). The test phase contained 120 new sequences, of which 60 were violations of the target grammar. Violations sequences were either non-configurational, i.e., they contained an incorrect number of stimuli (e.g., *AABBB*) or linear configurational, i.e., they violated the order in which *A* and *B* classes occurred (e.g., *BBBAAA*) or had too many transitions between classes (e.g., *ABBABA*). Each symbol (A or B) was mapped to a nonsense shape. Stimuli of class A were blue and rounded, and stimuli of class B were red and angled (Fig. 2). WR was asked to decide whether stimuli fit or did not fit the training set. He made his decisions using a computer mouse with a green and a red button.

Figure 2. Visual stimuli used in the experiment. Stimuli of class A were blue and rounded. Stimuli of class B were red and angled.



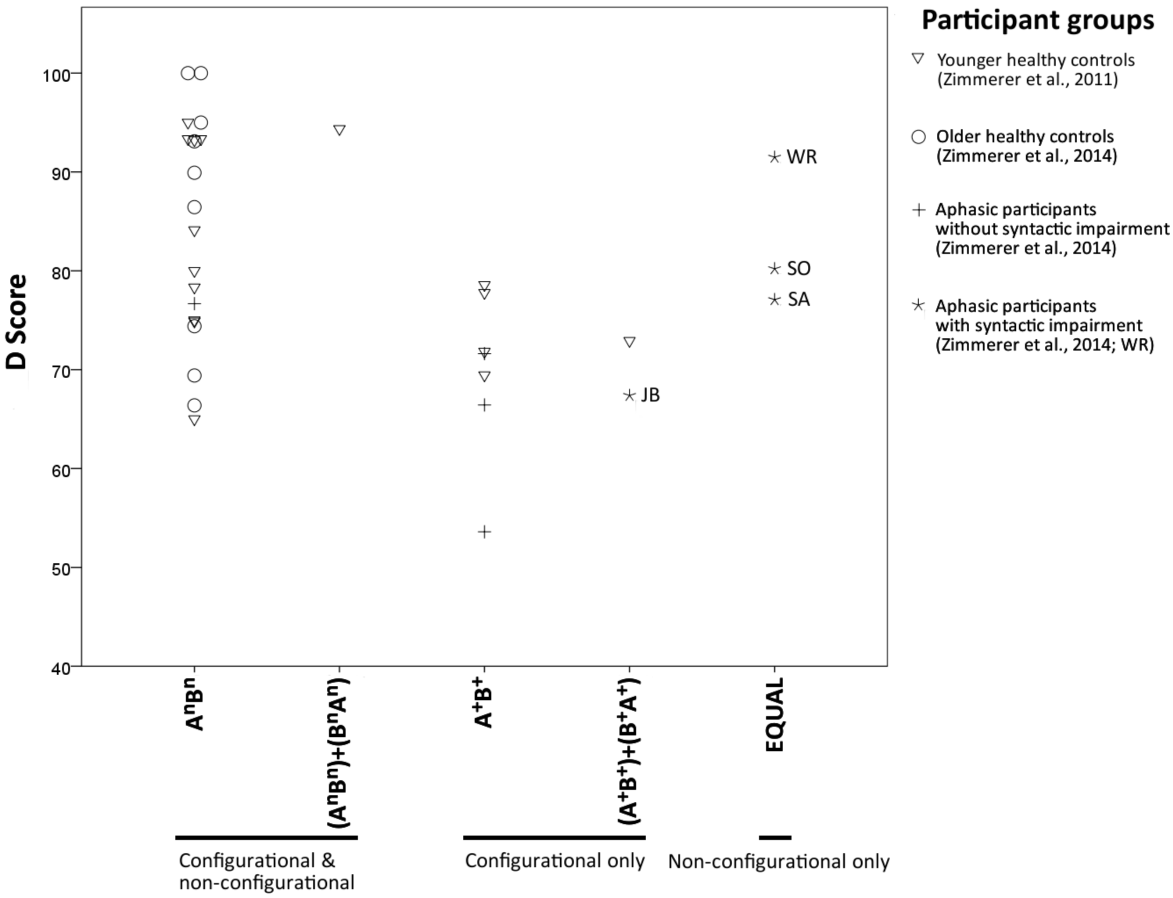
Results

At the start of the test phase, WR expressed uncertainty as to what was required. The experiment was paused and instructions repeated. As a result, he did not provide responses to the first three trials (two violations, one grammatical sequence). After instructions were repeated WR indicated he understood the task and responded quickly after each sequence. Ignoring the missed trials, WR accepted 96.6% (57/59) of the grammatical sequences. He rejected 50% of violations. However, classified by configurational (order) vs. non-configurational (counting) violations, he rejected 17% (6/35) of the former and 100% (23/23) of the latter (see online supplement for further details).

In AGL tasks it is possible that participants respond on the basis of familiarity of single stimuli or stimulus combinations, with a bias towards combinations that appeared more frequently. Such statistical sensitivity is likely part of configurational processing. To account for such behavior we calculated three familiarity variables for each test sequence (Knowlton & Squire, 1994; Redington & Chater, 1996): associative chunk strength (the mean frequency in which bigrams and trigrams appeared during training), anchor strength (the mean frequency in which initial and final bigrams and trigrams appeared at the respective positions during training) and chunk novelty (the number of bigrams and trigrams which did not appear during training). We then ran a logistic binary regression with acceptance/rejection of each sequence as a binary outcome variable. The predictors were the three familiarity variables as well as the categorical variable Sequence Type. A test of the full model was statistically significant, indicating that the predictors distinguished between acceptance and rejection of sequences, χ^2=75.649, p<.001, df=8. Nagelkerke's R^2 of .707 indicated a moderately strong relationship between prediction and response grouping. Only Sequence Type made a significant contribution to prediction, Wald=32.194, p<.001. Familiarity variables made no significant contribution.

Zimmerer, Cowell et al. (2011, 2014) applied a template analysis to explore the use of different acceptance/rejection criteria by participants. The template analysis describes a number of possible grammaticality criteria (summarized here as configurational only, non-configurational only, or both configurational and non-configurational). For instance, to test whether participants only rejected configurational violations, the analysis classifies not only A^nB^n sequences, but also non-configurational violations as grammatical, and all other sequences as ungrammatical. For each template, a D Score (see also Perruchet & Pacteau, 1990) was calculated by subtracting the percentage of grammatical sequences rejected from the percentage of ungrammatical sequences rejected. D Scores range from -100 to 100, with 100 representing fully consistent application of grammaticality criteria and zero representing chance. In addition, we used binomial tests to see if the proportions of accepted and rejected sequences deviated significantly from chance. We compared WR's scores with previously collected data from four severely aphasic participants with syntactic disorder, five aphasic participants without syntactic disorder, ten older and 20 younger controls. WR's D Score for the non-configurational template was 91.5, his score for configurational only was -13, and his score for the combined criteria was 46.6. WR, along with two severely aphasic participants (SA and SO), were the only participants who consistently rejected non-configurational violations and at the same time accepted configurational violations. One other severely aphasic participant, JB, showed some sensitivity to linear configuration.

Figure 3. Behavioral patterns across all test phase sequence types for healthy speakers aged below 50 years (mean age 27), healthy speakers aged 50 or older (mean age 62), aphasic participants without syntactic impairment, aphasic participants with severe syntactic impairment and WR. Each data point represents one participant (chance performances excluded). Categories indicate analysis template with highest D Score and suggest each participant's acceptability criteria. Higher D Scores indicate consistent application of decision criteria. Decision criteria: A^nB^n (configurational and non-configurational: A number of *A*s is followed by the same number of *B*s), $(A^nB^n)+(B^nA^n)$ (configurational and non-configurational: All items of one class precede all items of the other class, equal number of *A*s and *B*s), A^+B^+ (configurational: All *A*s precede the *B*s), $(A^+B^+)+(B^+A^+)$ (configurational: All items of one class precede all items of the other class) and EQUAL (non-configurational: Equal number of *A*s and *B*s).



Discussion

Impaired sentence processing has been associated with poor or atypical AGL performance. However, few studies have attempted to explore which aspects of sequence processing in AGL relate to which types of constructions. WR's very selective comprehension impairment provided a unique opportunity to explore the cognitive mechanisms involved in processing sentences that imposed greater loading on constituent-order processing, as is the case with English active sentences. These sentences are frequently employed in clinical comprehension tests. WR's AGL behavior shows a clear dissociation between his ability to spontaneously learn linear configurational and non-configurational information. He was very sensitive to quantitative properties of stimulus sequences and reliably rejected quantitative violations, but appeared insensitive to properties of stimulus order and consistently accepted order violations. In contrast, participants without syntactic disorder (healthy and aphasic) are more sensitive to linear configurational structure. In combination with his selective impairment of active sentence comprehension WR's data are consistent with claims that there is a relationship between AGL and sentence processing. His insensitivity to linear order in AGL may be related to his difficulties with processing English actives which rely on configuration rather than functional morphology.

One other AGL study has looked at individual aphasic profiles. WR's AGL behavior to date has only been observed in SA and SO, two people with severe syntactic disorder (Fig. 3, Zimmerer, Cowell et al., 2014) and large lesions across left perisylvian areas. However, SA and SO displayed chance level comprehension across both active and passive sentences. One possibility is that impairments of processing functional morphology in addition to failure of general configurational processing might be responsible for wholesale sentence processing failure. JB, another severely aphasic participant, was able to identify violations of configuration. However, in addition to a grammatical profile comparable to SA and SO, JB showed markedly lower lexical capacity (e.g., more impaired in naming and auditory/written synonym judgment (see Zimmerer, Cowell, & Varley, 2014, for his full profile). It is possible that this severe lexical impairment masked intact configurational processing in natural language processing.

It is not possible to generalize from a few cases to populations, and further investigations are needed. However, consistent reports of heterogeneity in agrammatism (Berndt & Caramazza, 1999; Caramazza, Capasso, Capitani, & Miceli, 2005; Caramazza, Capitani, Rey, & Berndt, 2001), warrant a focus at individual profiles. WR's profile is consistent with a claim of impaired configurational processing, accounting for his difficulty processing active, but not passive, sentences. We suggest the following hypotheses for further investigations:

1. Participants who are insensitive to configuration in AGL will have difficulties (at least) with sentences which are word order reliant, at least in comprehension.

2. Participants who have no difficulties with processing word order in language (when functional morphology is absent) will show a typical profile with regard to linear configurational processing in AGL.

The hypotheses also underline questions which, because of the progressive nature of WR's pathology, could not be addressed in the current report. For instance, our explanations predict difficulties with object-clefts as well subject-auxiliary inversions. Similarly, sensitivity to ungrammatical word order can be tested in the future via grammaticality judgment tasks, and it would be expected that a participant with WR's profile would fail to recognize such violations. However, the relationship between configurational processing in AGL and natural language processing may differ from language to language. In languages with a less rigid word order and/or more functional morphology, impaired configurational processing may result in less severe linguistic impairment. In other languages, such impairment may not affect actives, but other constructions.

[1] Early reports suggested that non-configurational properties of A^nB^n were processed through hierarchical phrase embedding (Fitch & Hauser, 2004; Friederici, Bahlmann, Heim, Schubotz, & Anwander, 2006). Some variations of A^nB^n, but not the one used for this experiment, aim to force hierarchical phrase processing (Bahlmann et al., 2008, 2009; Lai & Poletiek, 2011).

References:

Bahlmann, J., Schubotz, R. I., & Friederici, A. D. (2008). Hierarchical artificial grammar processing engages Broca's area. *NeuroImage*, *42*, 525–534.

Bahlmann, J., Schubotz, R. I., Mueller, J. L., Koester, D., & Friederici, A. D. (2009). Neural circuits of hierarchical visuo-spatial sequence processing. *Brain Research*, *1298*, 161–170.

Berndt, R. S., & Caramazza, A. (1999). How "Regular" Is Sentence Comprehension in Broca's Aphasia? It depends on how you select the patients. *Brain and Language*, *67*(3), 242–247.

Boeckx, C., Martinez-Alvarez, A., & Leivada, E. (2014). The functional neuroanatomy of serial order in language. *Journal of Neurolinguistics*, *32*, 1–15.

Brooks, P. J., & Tomasello, M. (1999). Learning the English passive construction. In B. Fox, D. Juracsky, & L. Moichaelis (Eds.), *Cognition and Function in Language*. Stanford, CA: CSLI Publication.

Caplan, D., & Waters, G. S. (1999). Verbal working memory and sentence comprehension. *Behavioral and Brain Sciences*, *22*, 77–126.

Caramazza, A., Capasso, R., Capitani, E., & Miceli, G. (2005). Patterns of comprehension performance in agrammatic Broca's aphasia: A test of the Trace Deletion Hypothesis. *Brain and Language*, *94*(1), 43–53.

Caramazza, A., Capitani, E., Rey, A., & Berndt, R. S. (2001). Agrammatic Broca's Aphasia Is Not Associated with a Single Pattern of Comprehension Performance. *Brain and Language*, *76*(2), 158–184.

Christiansen, M. H., Louise Kelly, M., Shillcock, R. C., & Greenfield, K. (2010). Impaired artificial grammar learning in agrammatism. *Cognition*, *116*(3), 382–393.

Conway, C. M., Bauernschmidt, A., Huang, S. S., & Pisoni, D. B. (2010). Implicit statistical learning in language processing: Word predictability is the key. *Cognition*, *114*(3), 356–371.

Conway, C. M., Karpicke, J., & Pisoni, D. B. (2007). Contribution of implicit sequence learning to spoken language processing: some preliminary findings with hearing adults. *Journal of Deaf Studies and Deaf Education*, *12*(3), 317–34.

Conway, C. M., & Pisoni, D. B. (2008). Neurocognitive basis of implicit learning of sequential structure and its relation to language processing. *Annals of the New York Academy of Sciences*, *1145*, 113–31.

De Vries, M. H., Monaghan, P., Knecht, S., & Zwitserlood, P. (2008). Syntactic structure and artificial grammar learning: The learnability of embedded hierarchical structures. *Cognition*, *107*(2), 763–774.

Dominey, P. F., Hoen, M., Blanc, J.-M., & Lelekov-Boissard, T. (2003). Neurological basis of language and sequential cognition: Evidence from simulation, aphasia, and ERP studies. *Brain and Language*, *86*(2), 207–225.

Drai, D., & Grodzinsky, Y. (2006). A new empirical angle on the variability debate: Quantitative neurosyntactic analyses of a large data set from Broca's Aphasia. *Brain and Language*, *96*(2), 117–128.

Druks, J. (2002). Verbs and nouns: a review of the literature. *Journal of Neurolinguistics*, *15*(3-5), 289–315.

Druks, J., & Marshall, J. C. (1995). When passives are easier than actives: two case studies of aphasic comprehension. *Cognition*, *55*, 311–331.

Druks, J., & Marshall, J. C. (1996). Syntax, strategies, and the single case: a reply to Zurif. *Cognition*, *58*, 281–287.

Ferreira, F. (2003). The misinterpretation of noncanonical sentences. *Cognitive Psychology*, *47*, 164–203.

Fitch, W. T., & Hauser, M. D. (2004). Computational constraints on syntactic processing in a nonhuman primate. *Science*, *303*, 377–380.

Friederici, A. D., Bahlmann, J., Heim, S., Schubotz, R. I., & Anwander, A. (2006). The brain differentiates human and non-human grammars: Functional localization and structural connectivity. *Proceedings of the National Academy of Sciences*, *103*(7), 2458–2463.

Gorno-Tempini, M. L., Hillis, A. E., Weintraub, S., Kertesz, A., Mendez, M., Cappa, S. F., … Grossman, M. (2011). Classification of primary progressive aphasia and its variants. *Neurology*, *76*(11), 1006–14.

Grodzinsky, Y. (2000). The Neurology of Syntax: Language Use Without Broca's Area. *Behavioral and Brain Sciences*, *23*, 1–71.

Hochmann, J.-R., Azadpour, M., & Mehler, J. (2008). Do Humans Really Learn AnBn Artificial Grammars From Exemplars? *Cognitive Science*, *32*(6), 1021–1036.

Hoen, M., Golembiowski, M., Guyot, E., Deprez, V., Caplan, D., & Dominey, P. F. (2003). Training with cognitive sequences improves syntactic comprehension in agrammatic aphasics. *NeuroReport*, *14*(3), 495–499.

Israel, M., Johnson, C., & Brooks, P. J. (2001). From states to events: The acquisition of English passive participles. *Cognitive Linguistics*, *11*(1-2), 103–129.

Kay, J., Lesser, R., & Coltheart, M. (1992). *Psycholinguistic Assessment of Language Processing in Aphasia*. Hove, U.K.: Psychology Press.

Kidd, E. (2012). Implicit statistical learning is directly associated with the acquisition of syntax. *Developmental Psychology*, *48*(1), 171–184.

Knowlton, B. J., & Squire, L. R. (1994). The information acquired during artificial grammar learning. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *20*(1), 79–91.

Lai, J., & Poletiek, F. H. (2011). The impact of adjacent-dependencies and staged-input on the learnability of center-embedded hierarchical structures. *Cognition*, *118*(2), 265–73.

Lum, J. A. G., Conti-Ramsden, G., Morgan, A. T., & Ullman, M. T. (2014). Procedural learning deficits in specific language impairment (SLI): A meta-analysis of serial reaction time task performance. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *51*, 1–10.

Mauner, G., Fromkin, V. A., & Cornell, T. L. (1993). Comprehension and acceptability judgments in agrammatism: Disruptuions in the syntax of referencial dependency. *Brain and Language*, *45*, 340–370.

Perruchet, P., & Pacteau, C. (1990). Synthetic Grammar Learning: Implicit Rule Abstraction or Explicit Fragmentary Knowledge? *Journal of Experimental Psychology: General*, *119*, 264–275.

Perruchet, P., & Rey, A. (2005). Does the mastery of center-embedded linguistic structures distinguish humans from nonhuman primates? *Psychonomic Bulletin & Review*, *12*(2), 307–313.

Petersson, K. M., Folia, V., & Hagoort, P. (2012). What artificial grammar learning reveals about the neurobiology of syntax. *Brain and Language*, *120*(2), 83–95.

Petersson, K. M., Forkstam, C., & Ingvar, M. (2004). Artificial syntactic violations activate Broca's region. *Cognitive Science*, *28*(3), 383–407.

Reber, A. S. (1967). Implicit Learning of Artificial Grammars. *Journal of Verbal Learning & Verbal Behavior*, *6*(6), 855–863.

Redington, M., & Chater, N. (1996). Transfer in artificial grammar learning: A reevaluation. *Journal of Experimental Psychology: General*, *125*(2), 123–138.

Riches, N. G. (2013). Treating the passive in children with specific language impairment: A usage-based approach. *Child Language Teaching and Therapy*, *29*(2), 155-169.

Thompson, C. K., Meltzer-Asscher, A., Cho, S., Lee, J., Wieneke, C., Weintraub, S., & Mesulam, M.-M. (2013). Syntactic and morphosyntactic processing in stroke-induced and primary progressive aphasia. *Behavioural Neurology*, *26*(1-2), 35–54.

Wechsler, D. (1999). *Wechsler Intelligence Scale for of Intelligence (WASI)*. San Antonio, TX: Harcourt Assessment.

Zimmerer, V. C., Cowell, P. E., & Varley, R. A. (2011). Individual behavior in learning of an artificial grammar. *Memory & Cognition*, *39*(3), 491–501

Zimmerer, V. C., Cowell, P. E., & Varley, R. A. (2014). Artificial grammar learning in individuals with severe aphasia. *Neuropsychologia*, *53*, 25–38.

Zimmerer, V. C., Dąbrowska, E., Romanowski, C. A. J., Blank, C., & Varley, R. A. (2014). Preservation of passive constructions in a patient with primary progressive aphasia. *Cortex*, *50*, 7–18.

Online supplement

Methods (extended)

We used the same methods as Zimmerer, Cowell and Varley (2011, 2014) to allow comparability with control and aphasic data reported therein (see online supplement for full Methods description). WR was tested in the visual modality, which is consistent with prior AGL research conducted on people with aphasia. WR participated in the AGL experiment two months after the reversible sentence comprehension test took place. WR gave informed consent to participation. Ethical approval was granted by the local NHS Research Ethics Committee (08/H1308/32).

Each symbol (A or B) was mapped to a nonsense shape. Stimuli of class A were blue and rounded, and stimuli of class B were red and angled (Fig. 2). For each class there were eight different shapes. Stimuli were presented one after another. Stimulus duration was 400 ms. The interstimulus interval was 200 ms within a sequence and 4.5s between sequences. Between sequences, a fixation cross appeared on the screen. The average trial length was 8 seconds.

The training phase consisted of 72 A^nB^n-sequences of three different structures: *AABB*, *AAABBB* and *AAAABBBB*. Each structure appeared 24 times. Each sequence had a unique combination of stimuli, and each stimulus appeared the same number of times. The test phase consisted of 60 new A^nB^n-sequences (grammatical) and 60 violation sequences (ungrammatical) that employed the same symbol sets. To enable identification of different response patterns, there were five types of violation sequences. Each violation type occurred 12 times. Two violated non-configurational, and three violated configurational properties of the grammar:

- Type 1 (non-configurational) had mismatching numbers of *A*s and *B*s*.* In addition, it had an odd total number of stimuli, while grammatical sequences always contain an even number. E.g., *AABBB*.
- Type 2 (non-configurational) had mismatching numbers of *A*s and *B*s but a (legal) even total number of stimuli, e.g., *AAAABB*.
- Type 3 (configurational) had the reverse class order. They started with the wrong class, ended with the wrong class and contained the ungrammatical combination *BA*, e.g., *BBBAAA*.
- Type 4 (configurational) started with the wrong class and contained the ungrammatical combination *BA*, e.g., *BABAAB*.

- Type 5 (configurational) ended with the wrong class and contained the ungrammatical combination *BA*, e.g., *ABBABA*.

Zimmerer, Cowell et al. (2011, 2014) employed the same randomized sequence order across all participants to eliminate order effects across individuals. The only randomization parameter was that not more than four consecutive test sequences were all grammatical or all ungrammatical. The same order was used for WR. The training and the test phase were each divided into three trial blocks of equal length, with a self-timed break between blocks. The entire session took ca. 25 minutes.

Decisions in the test phase were made via a computer mouse. The left button was marked with a green sticker, the right button with a red sticker. The green button registered acceptance, and the red button rejection of a sequence. There was a timeout after 4.5 seconds. Before the training phase, WR was instructed to attend to the stimuli on the screen. Instructions were simplified and presented in writing (Zimmerer, Cowell et al., 2014). Before the training phase, we asked WR to watch the screen. Before the test phase, we presented him instructions on paper in a 26pt font: "Now you will see more shapes. Do they follow the pattern of the shapes you just saw? GREEN button – YES – same pattern. RED button – NO – different pattern. Decide quickly." There was a line break before each new sentence. The word "green" was printed in green font, the word "red" in red font. The experimented provided the instructions orally, supported by gestures ("thumbs up", "thumbs down"). WR signaled that he understood the instructions before proceeding.

Results (extended)

At the start of the test phase, WR expressed uncertainty as to what was required. The experiment was paused and instructions repeated. As a result, he did not provide responses to the first three trials (type 1 violation, grammatical sequence, type 5 violation, in that order). After instructions were repeated WR indicated he understood the task and responded quickly after each sequence. Ignoring the missed trials, WR accepted 96.6% (57/59) of the grammatical sequences. He rejected 100% (11/11) of the violations of type 1, 100% (12/12) of the violations of type 2, 0% (0/12) of the violations of type 3, 8% (1/12) of the violations of type 4 and 45% (5/11) of the violations of type 5. Classified by configurational (order) vs. non-configurational (counting) violations, he rejected 17% of the former and 100% of the latter.

In AGL tasks it is possible that participants respond on the basis of familiarity of single stimuli or stimulus combinations, with a bias towards combinations that appeared more frequently. Such statistical sensitivity is likely part of configurational processing. To account for such behavior we calculated three familiarity variables for each test sequence (Knowlton & Squire, 1994; Redington & Chater, 1996): associative chunk strength (the mean frequency in which bigrams and trigrams appeared during training), anchor strength (the mean frequency in which initial and final bigrams and trigrams appeared at the respective positions during training) and chunk novelty (the number of bigrams and trigrams which did not appear during training). We then ran a logistic binary regression with acceptance/rejection of each sequence as a binary outcome variable. The predictors were the three familiarity variables as well as the categorical variable Sequence Type (six categories: violation types 1-5, grammatical). Logistic regressions cannot converge if categories are completely full or empty and, as for some cases in Zimmerer, Cowell et al. (2014), we added or subtracted one rejection from a category if it was full or empty. As a result, the regression assumed that one violation of type 1 and type 2 was accepted, and that one violation of type 3 was rejected. Note that this necessary operation results in an underestimation of the effect of sequence type. A test of the full model was statistically significant, indicating that the predictors distinguished between acceptance and rejection of sequences, χ^2=75.649, p<.001, df=8. Nagelkerke's R^2 of .707 indicated a moderately strong relationship between prediction and response grouping. Only Sequence Type made a significant contribution to prediction, Wald=32.194, p<.001. Familiarity variables made no significant contribution.

Zimmerer, Cowell et al. (2011, 2014) applied a template analysis to explore the use of different acceptance/rejection criteria by participants. The template analysis describes a number of possible grammaticality criteria (summarized here as configurational only, non-configurational only, or both configurational and non-configurational). For instance, to test whether participants only rejected configurational violations, the analysis classifies not only A^nB^n sequences, but also sequences of violation types 1 and 2 as grammatical, and all other sequences as ungrammatical. For each template, a D Score (see also Perruchet & Pacteau, 1990) was calculated by subtracting the percentage of grammatical sequences rejected from the percentage of ungrammatical sequences rejected. D Scores range from -100 to 100, with 100 representing fully consistent application of grammaticality criteria and zero representing chance. We compared WR's scores with previously collected data from four severely aphasic participants with syntactic disorder, five aphasic participants without syntactic disorder, ten older and 20 younger controls. WR, along with two severely aphasic participants (SA and SO), were the only to consistently reject non-configurational violations but accepted configurational violations. One other severely aphasic participant, JB, showed some sensitivity to configuration.

References:

Zimmerer, V. C., Cowell, P. E., & Varley, R. A. (2011). Individual behavior in learning of an artificial grammar. *Memory & Cognition*, *39*(3), 491–501

Zimmerer, V. C., Cowell, P. E., & Varley, R. A. (2014). Artificial grammar learning in individuals with severe aphasia. *Neuropsychologia*, *53*, 25–38.