THE ROLE OF VERBAL SHORT-TERM MEMORY IN COMPLEX SENTENCE COMPREHENSION: AN OBSERVATIONAL STUDY ON APHASIA

ABSTRACT

Background: The comprehension profile of people with agrammatism is a debated topic. Syntactic complexity and cognitive resources, in particular phonological short-term memory (pSTM), are considered as crucial components by different interpretative accounts.

Aim: The aim of the present study was to investigate the interaction of syntactic complexity and of pSTM in sentence comprehension in a group of persons with aphasia with and without agrammatism.

Methods & Procedures: A cohort of 30 participants presenting with aphasia was assessed for syntactic comprehension and for pSTM. Fifteen presented with agrammatism and 15 had fluent aphasia.

Outcomes & Results: Linear nested mixed-model analyses revealed a significant interaction between sentence type and pSTM. In particular, participants with lower pSTM scores showed a reduced comprehension of center-embedded object relatives and long coordinated sentences. Moreover, a significant interaction was found between sentence type and agrammatism, with a lower performance for passives within the agrammatic group.

Conclusions & Implications: These results confirm that pSTM is involved in the comprehension of complex structures with an important computational load, in particular coordinated sentences, and long-distance filler gap dependencies. On the contrary, the specific deficit of the agrammatic group with passives is a pure syntactic deficit, with no involvement of pSTM.

Data Availability Statement

https://osf.io/6xw7y/?view_only=7f033c99deda489eba71c2f22ffd00d0

Key words: phonological short-term memory, sentence comprehension, aphasia, agrammatism

Word count: 5400

1) *What is already known on this subject*: The characteristics of verbal production in people with agrammatism are fairly well described while their comprehension profile is much more controversial. Different interpretative accounts have been proposed, some focusing on the syntactic complexity while others considering the role of cognitive resources, phonological short-term memory in particular, as crucial elements for sentence comprehension. Experimental evidence provided contrasting results supporting either these hypotheses and leaving the debate open. Recently, integrated approaches tried to analyze the joined role of these two factors in predicting sentence comprehension performance.

2) *What this study adds*: The novelty of our contribution is not the research question, which has been at the center of the debate on agrammatism for a long time, but in the way we answer it, namely by controlling the predictive power of both syntactic complexity and pSTM demand for comprehension of different types of sentences. Our results confirm that passive sentences are the most sensitive detector for agrammatism. On the contrary, comprehension deficits with sentence coordination can be mostly imputed to pSTM deficits. Finally, difficulties with object relatives and center embedding seem to be determined both by structural and resource-based factors.

3) *Clinical implications of this study*: The relation between pSTM, syntactic complexity and sentence comprehension has crucial implications for theoretical models, diagnosis, treatment, and communication strategies for people with aphasia. First, a better understanding of the source of language comprehension deficits would allow a precise characterization of the language profile and the development of extensive and sophisticated assessment tools. Second, this would allow to identify the priorities of clinical interventions focusing on memory impairments and/or on linguistic dysfunctions. A third, final implication concerns the development of effective strategies to communicate with people with aphasia, maximizing their abilities to understand discourse.

1. INTRODUCTION

The production profile of people with agrammatism is fairly well understood. They produce only short utterances with a very limited, or no presence at all, of closed class words (articles, auxiliaries, prepositions etc.) and bound morphemes. Their comprehension profile is much more controversial. Starting from Caramazza and Zurif's (1976) seminal paper, it became clear that a subgroup of people with agrammatism (Caramazza et al., 2005) have comprehension problems with sentences in which a full grammatical analysis is necessary for meaning extraction. In order to clarify when a full grammatical analysis is necessary consider sentence (1). In (1) and in the following sentences, we indicate the presence of a gap by '*e*' (for empty category) and we indicate the category the gap depends on (the filler) by co-indexation. Although the postulation of a gap (also called 'trace' or 'copy') and the related notion of syntactic movement are typical of the generative framework (cf. Adger 2003 for a textbook presentation), which we assume here for concreteness, what is essential for our purposes in this paper is the rather uncontroversial assumption that there are syntactic dependencies between noncontiguous categories.

(1) The gallerist_1 that the artist hates e_1 is in the last room
(2) The painting_1 that the artist did e_1 is in the last room

What makes (1) more challenging than (2) is that world knowledge is not enough to understand which noun is modified by the relative clause, since an artist can hate a gallerist but the other way around is possible too. In (2), on the other hand, world knowledge (or more precisely, principles governing thematic roles assignment to animate and inanimate entities) makes sure that the noun modified by the relative clause is 'painting'. Therefore, meaning extraction requires full grammatical analysis in (1), crucially including the computation of the long-distance dependency between the filler ('gallerist') and the gap, which is to be identified with the object position inside the relative clause.
Importantly, an object relative like (1) is typically more challenging, including for people with agrammatism, than a subject relative like (3):

(3) The gallerist_1 that e_1 hates the artist is in the last room

There are different possible reasons for this pattern. A simple explanation is that (3) can be understood by applying a simple canonicity heuristic that, at least for languages that have a default Subject Verb Object order, dictates that the first noun phrase corresponds to the agent, and the second one to the patient (much like in the corresponding simple sentence 'The gallerist hates the artist'). Therefore, (3), like (2), although for different reasons, can be understood even in the absence of a full grammatical analysis. Although canonicity is likely to help people with a grammatical deficit to respond correctly in tasks like sentence to picture matching, a consistent set of findings from the psycholinguistics literature shows that this explanation is not sufficient. In particular, both in the general population, and in young children it has been shown that not all types of object relatives are equally complex, for example the relative 'the gallerist_1 that he hates e_1' is much easier than 'the gallerist_1 that the artist hates e_1'. This type of finding cannot be explained by the canonicity heuristic. To see another source of difference between subject and object relatives, consider again (1) and (3). In (1) when the gap is met in on-line processing, there are two possible candidates as filler: the intended filler ('gallerist') and the other noun 'artist'. The latter intervenes in the filler gap dependency (cf. Friedmann et al. 2009 and Gordon et al. 2004 for two different ways to operationalize the interference caused by intervention). However, in (3) no such intervention arises, as no noun phrase intervenes between filler and gap. While in the general population, the cost of processing intervention becomes visible only in subtle on-line measures, in people with aphasia (and in young children) intervention may impair filler gap dependency processing and lead to a comprehension problem.
To complete the picture, consider that in (1) there is another source of complexity, in addition to the interference caused by subject intervention. In fact, in addition to the filler gap dependency, another long-

distance dependency must be processed, namely the one between the main subject ('the gallerist') and the main verb, which in (1) is the copula that agrees with the main subject. Processing this dependency is potentially challenging since the relative clause interposes between the matrix subject and the matrix verb (technically it is 'center embedded'). While in (1) the processing complication caused by intervention adds to the processing complication caused by center embedding, sentences like (4), in which there is right branching relative, have the former complication but not the latter.

(4) The journalist meets gallerist$_1$ that e_1 hates the artist

Going back to the characterization of agrammatism, the identification of a comprehension deficit in this population suggested that there is a common neural substrate for the deficits in production and comprehension. In particular, this suggested that the brain region which is typically damaged in people with agrammatism, namely Broca's area (more specifically BA44/45), might be the locus of syntactic operations (cf. Grodzinsky and Santi 2008 for a review).

However, this view has been challenged. For one thing, the comprehension deficit exemplified by sentences like (1) is not specific to agrammatism. In fact, already Caramazza and Zurif (1976) reported that it extends to conduction aphasia.

Second, subsequent work suggests a more complex pattern by which damage to Broca's area is not necessary for the presence of agrammatism (Fridriksson, Bonilha and Rorden, 2007), and damage circumscribed to Broca's area may not be sufficient to elicit it (Fridriksson *et al.*, 2015).

Third, neuroimaging and brain stimulation techniques that became available over time indicate that BA 45/47 might be equally or even more central to syntactic computations than BA 44 (cf. Pallier, Devauchelle and Dehaene, 2011 and Tyler *et al.*, 2010 but see Friederici *et al.*, 2006 for defense of the claim concerning the main role of BA 44).

Finally, people without agrammatism but with selective pSTM deficits (Vallar and Baddeley, 1984; Friedrich et al., 1985; Papagno et al. 2007) are severely impaired with center embedded relatives as in (1), although their performance is less impaired in the other types of relatives and with passive sentences. Therefore, the agrammatic comprehension deficit with center embedding might result from a pSTM deficit rather than from impaired grammatical knowledge (Badecker and Caramazza 1985). Consistently with this hypothesis, several studies have shown that BA 44 is involved in phonological short-term memory (pSTM), being the neural correlate of the articulatory rehearsal component (cf. Romero Lauro, Walsh and Papagno, 2006, Romero Lauro et al. 2010, and Papagno *et al.*, 2017).

In this paper, we reevaluate the claim that agrammatism can be associated to a specific sentence comprehension profile. We do that by adopting the following logic: if the agrammatic deficit with long dependencies (including filler-gap dependencies) is due to degraded pSTM, the performance with these sentences should be modulated by the pSTM span. Furthermore, the comprehension should be better with passives like (5), as the filler gap dependency is short and not affected by intervention. Therefore, passives are less challenging for pSTM.

(5) The gallerist$_1$ is hated e_1 by the artist

If, on the other hand, people with agrammatism have a grammatical deficit independent from a pSTM deficit, their pattern with passives should remain degraded and should be unaffected by their pSTM span.

Although passives have been heavily discussed in the literature on agrammatic comprehension, their status for the agrammatic population is still controversial (cf. Druks and Marshall, 1995 and Grodzinsky, 2000).

In order to deal with this research question, we involved fifteen participants with a clinical diagnosis of agrammatism and fifteen with a clinical diagnosis of fluent aphasia in a digit span task and in the standardized battery "Comprendo" (Cecchetto, Di Domenico, Garraffa, and Papagno, 2012), which measures comprehension of simple and complex syntactic structures in Italian.

2. DATA AVAILABILITY

https://osf.io/6xw7y/?view_only=7f033c99deda489eba71c2f22ffd00d0

3. METHODS AND MATERIAL

3.1 Participants

A cohort of 30 first-ever-stroke participants (15 male and 15 female) presenting with aphasia (time post onset > 3 months) was recruited in the Department of Neurorehabilitation Science of an in-patient rehabilitation facility in Milan, Italy. Inclusion criteria were: (a) diagnosis of left hemisphere damage confirmed by neuroimaging data; (b) presence of aphasia according to clinical evaluation; c) chronological age ranging from 20 to 85 years; (d) at least 8 years of education; (e) absence of severe hearing or visual impairments. Participants with severe comprehension impairment (Token Test score <10) and moderate to severe word comprehension deficits (accuracy <70% at the word comprehension tasks of the BADA, Miceli *et al.*, 1994) were excluded from the study. Participants were all Italian native speakers. Participants with non-fluent agrammatic aphasia or fluent aphasia were recruited. Classification of aphasia was made by an experienced team of clinicians through an extensive linguistic assessment, including the Token Test (De Renzi and Faglioni, 1978) and the BADA (Miceli et al., 1994). The participants' mean age was 67.00 (SD=11.21) years, with an average number of years of formal education of 12.63 (SD=3.25). The Token Test mean score was 19.48 (*SD*=5.48) while the mean accuracy on the BADA word comprehension subtest was 97.73 (*SD*=2.78). Within the sample, 16 participants (53%) showed a pathological digit span score (<4.26). Fifteen participants (50%) clinically presented with a non-fluent aphasia with agrammatism while the remaining 50% showed a fluent aphasia. The group with non-fluent agrammatism did not differ from the fluent group concerning gender, educational level, aphasia etiology and aphasia severity (as assessed by means of the Token Test and Word Comprehension), while the two groups significantly differed in age. Results are reported in **Table 1**.

Twenty-one participants (70%) suffered an ischemic stroke, 7 (23.3%) hemorrhagic, while one (3.3%) underwent low-grade glioma resection; the last participant (3.3%) had a fronto-parietal lesion secondary to an infective pathology. Lesion site was assessed for 25 out of the 30 included participants by CT or MRI scan and plotted manually through the open-source rendering software MRIcroGL (https://www.nitrc.org/projects/mricrogl/). Each image was than reconstructed on a standard template (MNI) using SPM12 software, which runs in MATLAB (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/). Scan images were not available for 5 people. Participants were divided into two groups considering the presence/absence of agrammatism.

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Local Ethics Committee (Milano Area B: Resolution 719_2019, ID 11111). Each participant gave informed written consent prior to the study.

Table 1. Demographic and clinical characteristics of the two groups of participants (non-fluent agrammatic vs. fluent). Continuous variables are reported as mean (*SD*), categorical as *N* (%).

	Agrammatic Group N=15 (50%)	Non-Agrammatic Group N=15 (50%)	Test
Gender			
Male	5 (33.3%)	10 (66.7%)	χ^2=3.333
Female	10 (66.7%)	5 (33.3%)	*p*=0.068
Etiology			
Ischemic Stroke	9 (60%)	12 (80%)	
Hemorrhagic Stroke	5 (33.3%)	2 (13.3%)	

Glioma resection *Brain Infection*	0 (0%) 1 (6.7%)	1 (6.7%) 0 (0%)	χ^2=3.714 *p*=0.294
Age	60.67 (±9.87)	73.33 (±8.77)	*t*=3.714 *p*<0.001
Education (years)	12.66 (±3.35)	12.60 (±3.26)	*t*=0.055 *p*=0.956
Token Test	19.20 (±5.93)	19.77 (±5.18)	*t*=0.279 *p*=0.783
Word Comprehension	98.46 (±2.29)	97.00 (±3.09)	*t*=1.475 *p*=0.151

3.2 Experimental tasks

Language task: the standardized Italian battery "Comprendo", a picture matching task involving the following ten types of sentences (100 stimuli total) was administrated (cf. Cecchetto *et al.,* 2012 for details):

1) active sentences (e.g., "La mamma sta inseguendo il bambino" - "The mum is chasing the boy");
2) dative sentences (e.g., "Il papa dà il cane alla bambina" - "The dad gives the dog to the girl");
3) passive sentences (e.g., "Il gatto$_i$ viene inseguito e_i dal cane" - "The cat$_i$ is chased e_i by the dog");
4) right branching subject relatives (e.g., "Il papà guarda il gatto$_i$ che e_i insegue il cane" - "The dad watches the cat$_i$ that e_i chases the dog");
5) right branching object relatives (e.g., "La mamma guarda il cane$_i$ che il bambino insegue e_i" - "The mum watches the dog$_i$ that the boy chases e_i");
6) center-embedded subject relatives (e.g., "Il cane$_i$ che e_i insegue il gatto guarda il nonno" - "The dog$_i$ that e_i chases the cat watches the grandpa");
7) center-embedded object relatives (e.g., "L'uomo$_i$ che la donna guarda e_i mangia la pasta" - "The man$_i$ that the woman watches e_i eats pasta");
8) coordination of complement NPs (e.g., "Il bambino insegue il cane e il gatto" - "The boy chases the dog and the cat");
9) coordination of VPs (e.g., "La bambina accarezza il gatto e insegue il cane" - "The girl caresses the cat and chases the dog");
10) sentence coordination (e.g., "Il papà tocca il gatto e il cane insegue il bambino" - "The dad touches the cat and the dog chases the boy").

In terms of the classification presented in the introduction, we can say that type 3 (passives), type 4 (right branching subject relatives) and type 6 (center-embedded subject relatives) contain filler gap dependencies without intervention. However, the filler gap dependencies in Type 5 (right branching object relatives) and type 7 (center-embedded object relatives) are characterized by intervention, with a possible processing cost.
Type 6 (center-embedded subject relatives) and type 7 (center-embedded object relatives) display center embedding, with a possible processing cost. Therefore, the only sentence type which combines the intervention cost and the center embedding cost is type 7. Finally, type 1, type 2, type 8, type 9 and type 10 do not contain either filler gap dependencies or center embedding. However, type 9, and type 10 even more, are long sentences and this might potentially impact pSTM.
Sentences were auditorily presented and participants were asked to point to the target picture among four. The three distractors included one picture with the inversion of thematic roles, one depicting the same characters but different actions and one unrelated stimulus (different characters and different actions).
One point was assigned for each correct response and the sum of all correct answers represented the total raw score that was corrected based on the participant's age and education. Each participant completed the task in one session (90 minutes) or two 45-minute sessions.
pSTM task: in order to evaluate the auditory pSTM, the Forward Digit Span (Monaco *et al.,* 2012) was used. The task ended when two sequences of the same length were not correctly reproduced, or after nine correct

series. The span corresponded to the longest series correctly repeated. All participants were assessed for the ability to orally repeat single digits before administering the Digit Span test. Motor speech disorders, when present, were mild and did not interfere with the task.

3.3 Statistical analysis

Statistical analyses were performed using the statistical programming environment R (R Development Core Team, 2019). Descriptive data were calculated as mean and SD or absolute number and frequency. In order to identify significant differences between the two groups, the χ^2 test and the Student's t test were adopted for categorical variables and for continuous variables respectively. The threshold for statistical significance was set at the conventional level α=0.05. For contrasts involving the Type factor, we considered a corrected level of $\alpha = .0056$, considering that Type had ten levels, thus implying nine contrasts. Linear mixed-effect models were performed as the main statistical procedure (Baayen, Davidson and Bates, 2008) using the R package *lme4* (Bates et al., 2015). The inclusion of fixed effects was tested with a series of likelihood ratio tests, to evaluate whether their inclusion increased the model goodness of fit (Baayen, Davidson and Bates, 2008; Gelman and Hill, 2006) using a forward stepwise inclusion method. With this procedure, the sentence type (scores from sentence type1 to type10), the presence of agrammatism (present vs absent), digit span scores and their interactions were tested as fixed factors. Concerning the random effect structure, the by-subject intercept was included. Individual models' *p*-values were estimated using the Satterthwaite's degrees of freedom approximation, as implemented in the *lmerTest* R package (version 2.0–29, Kuznetsova, Brockhoff and Christensen, 2015). Contrast analyses were additionally performed.

4. RESULTS

Means and standard deviations of the performance on each type of sentence and on the digit span of the overall sample and separated for the two groups are reported in **Table 2**.

A series of nested linear mixed models of increasing complexity was performed in order to predict the power of all the independent variables on participants' syntactic comprehension abilities. The results of this procedure are summarized in **Table 3.**

Table 2. Performances, reported as mean (SD) of the overall sample and the two groups on the 10 different types of sentences and the digit span task.

	Overall Sample N=30	Agrammatic Group N=15 (50%)	Non-Agrammatic Group N=15 (50%)
Type 1 - active	92,13 (±8,11)	90,13 (±9,53)	94,13 (±6,06)
Type 2 - dative	88,67 (±10,42)	86,67 (±11,13)	90,67 (±9,61)
Type 3 - passive	77,02 (±18,34)	65,80 (±18,66)	88,23 (±8,88)
Type 4 - right branching subject relative	84,93 (±10,16)	81,93 (±10,48)	87,93 (±9,20)
Type 5 - right branching object relative	63,97 (±15,92)	60,90 (±13,89)	67,03 (±17,67)
Type 6 - center-embedded subject relative	71,80 (±11,98)	68,33 (±11,01)	75,27 (±12,25)
Type 7 - center-embedded object relative	60,18 (±16,39)	52,27 (±11,96)	68,10 (±16,71)

Type 8 - coordination of complement NPs	78,92 (±16,21)	77,77 (±17,87)	80,07 (±14,91)
Type 9 - coordination of VPs	77,80 (±14,82)	78,00 (±14,32)	77,60 (±15,81)
Type 10 - sentence coordination	80,50 (±14,45)	78,17 (±14,45)	82,83 (±14,56)
Digit Span Forward	4,27 (±1,16)	3,78 (±0,89)	4,75 (±1,22)

Table 3. Summary of the linear mixed models of increasing complexity predicting the effect of age, sentence type, agrammatism and pSTM on syntactic comprehension abilities. Models are represented using the *lme4* formula syntax (Bates et al., 2015).

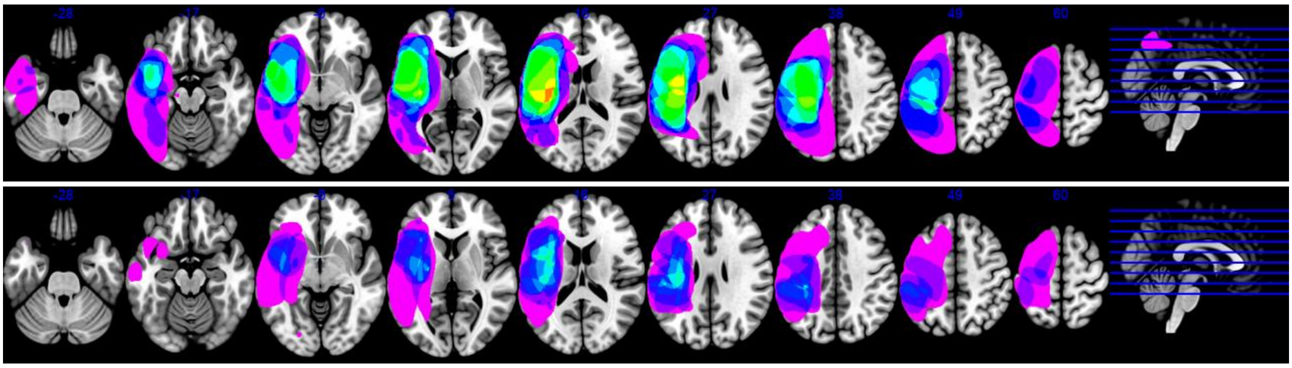
Model 1	Comprehension ~ Age + Type + (1|N)		
	AIC	χ^2	*P*
	2378.8	-	-
Model 2	Comprehension ~ Age + Type + Agrammatism + (1|N)		
	AIC	χ^2	*P*
	2376.2	4.584	0.032
Model 3	Comprehension ~ Age + Type * Agrammatism + (1|N)		
	AIC	χ^2	*P*
	2367	26.447	0.002
Model 4	Comprehension ~ Age + Type * Agrammatism + pSTM + (1|N)		
	AIC	χ^2	*P*
	2349.3	20.393	<0.001
Model 5	Comprehension ~ Age + Type * Agrammatism + Type * pSTM + (1|N)		
	AIC	χ^2	*P*
	2343.4	23.891	0.004
Model 6	Comprehension ~ Age + Type * Agrammatism + Type * pSTM + (1|N)		
	AIC	χ^2	*P*
	2358.8	4.618	0.915

The likelihood ratio test and the Akaike Information Criterion (AIC) indicated that model 5, including all the independent variables and their interactions, but excluding a three-way interaction between Type, Agrammatism and pSTM, showed the best fit (Table 3). The analysis revealed significant main effects of sentence type, $F(9,243)=5.167$, $p<0.001$, and digit span $F(1,26)=25.309$, $p<0.001$, while the main effects of age and agrammatism per se were not significant (both *p*s > 0.43). Importantly, the interaction effect between sentence type and agrammatism was significant, $F(9,243)=2.786$, $p=0.004$. In particular, the contrast analysis showed a significant interaction effect for passive sentences (Type3), $t(243)=2.880$, $p=0.0047$, indicating lower scores in passive sentences within the agrammatic group ($M=65.80$, $SD=18.66$) than in the non-agrammatic group ($M=88.23$, $SD=8.88$). None of the other contrasts reached significance (all *p*s>0.21). Moreover, a significant interaction effect was found between sentence type and pSTM, $F(9,243)=2.498$, $p=0.009$. The interaction was significant for center-embedded object relatives (Type7), $t(243)=2.654$, $p=0.008$, and for sentence coordination (Type10), $t(243)=3.213$, $p=0.001$, with participants with a lower STM score showing more difficulties with this kind of syntactic constructions (center-embedded object relatives and coordination of sentences, respectively). None of the other contrasts reached significance (all *p*s>0.08). Post-hoc analyses were performed to compare agrammatic vs. non-agrammatic groups and each type of sentence in the two groups separately (see **Supplementary Material**).

Concerning the anatomical aspects, overlapped lesion maps of the agrammatic group showed that in 8 out of 11 participants, the lesions superimposed in the left insula and in the left Rolandic operculum while in the non-agrammatic group, in 11 out of 14 participants, the lesions superimposed in the left insula and in the left Heschl gyrus. Therefore, there was only a minimal distinction, being the insula involved in both groups. The only difference was that in the non-fluent group the lesion extended more anteriorly in the frontal lobe, and in the fluent one posteriorly in the temporal lobe. Overlapped lesion maps of the two groups are shown in **Figure 1**.

Figure 1.

Superimposition of the left-hemispheric lesions in the 11 people with agrammatism (**A**) and in the 14 people without agrammatism (**B**). MNI coordinates for the shown axial slice are given. The number of overlapping lesions is illustrated by different colors coding increasing frequencies from violet (n=1) to red (n=max number of subjects).



5. GENERAL DISCUSSION

The present observational study assessed the respective contributions (if any) of impaired morphosyntax and pSTM to the agrammatic profile. Fifteen people clinically diagnosed with agrammatism and fifteen fluent ones were included. All participants underwent both the digit span task and the “Comprendo” battery. The “Comprendo” battery includes sentences that vary for the presence/absence of filler gap dependency (passives and sentences with relative clauses as opposed to all the others), for the presence/absence of an intervening element in filler gap dependency (object relatives versus passives and subject relatives), for the presence/absence of center embedding and for their overall length. We focus here on sentences with non-canonical order, since in these sentences the people with aphasia could not adopt the canonicity heuristic ‘the first noun phrase is the agent, the second one is the patient’, in so doing by-passing the need to perform a full grammatical analysis.

In this respect, a most informative case involves the comparison between object relatives and passives since they both involve a filler gap dependency that cannot be resolved by the aforementioned canonicity heuristic. In this respect, they are both syntactically complex, where syntactic complexity for our present goals can be operationalized as presence of a filler-gap dependency.

However, object relatives are affected by intervention, while passives are not, at least prima facie. For example, in sentence (1) above (‘The gallerist that the artist hates is in the last room’) in principle two noun phrases (‘the gallerist’ and ‘the artist’) compete as possible fillers for the gap position. A correct performance in the sentence to picture matching task requires the resolution of the intervention configuration, namely the retrieval of the filler between the two competitors. We assume that this process involves pSTM (cf. Papagno and Cecchetto 2019 for a defense of the role of pSTM in on-line processing of complex syntactic dependencies and Caplan et al. 1999 for the claim that pSTM’s role is limited to post-interpretative stages).

Therefore, the comparison between these two types of sentences could clarify the contribution of memory resources and syntactic abilities to the comprehension profile of people with agrammatism. We stress that the novelty of our contribution is not the research question, which has been at the center of the debate on agrammatism for a long time (cf. Grodzinsky et al., 1999; Caramazza et al., 2005), but in the way we answer it, namely by controlling with precision the level of all the independent variables on two controlled groups of fluent and agrammatic participants. In fact, by analyzing the effects of the interactions between sentence type and both agrammatism and pSTM, we could establish that passives are the only type of sentence that truly distinguishes agrammatic from fluent group, as the comprehension of passives is not modulated by pSTM resources. This confirms the primacy of a grammatical deficit (or access to grammatical knowledge) in agrammatism. Indeed, the role of pSTM in the comprehension of passives is negligible since the filler-gap dependency is very short and no intervention occurs.

Moving now to the contrast analyses, lower pSTM scores were predictive of worse performances with coordination of sentences (type 10) and with center-embedded object relatives (type 7). This is in line with what observed in single case reports and in studies using rTMS (see Papagno and Cecchetto, 2019 for a review). Indeed, an impairment in center-embedded relatives seems to be a constant finding in people with a pSTM deficit, contrary to some claim in the literature (Martin and He, 2004). This finding also confirms that pSTM plays a crucial role in sentence comprehension when the syntactic structure is sufficiently challenging. Type 7 sentences are challenging because they combine the intervention factor and the center embedding factor, while type 10 sentences are challenging because they are the only case of coordination of two full and independent sentences that must be temporarily stored in memory. Interestingly, sentence length cannot explain alone the predictive role of pSTM in sentence comprehension, as the center-embedded object relatives are shorter than the coordination of sentences in our stimuli, syntactic complexity defined as above being the other area in which the role pSTM is critical. That type 7 are shorter than type 10 sentences was verified by considering both phonological features (number of phonemes and number of syllables are statistically lower in type 7) and morphological characteristics (number of morphemes and number of words are consistently lower in type 7, with no variance).

However, both groups perform better with type 10 than with types 7 (post-hoc analyses - agrammatic group: χ^2=41.75, $p<0.001$; non-agrammatic group: χ^2=11.56, p=0.036), although the former are longer. This confirms the importance of the internal structure of sentences in tasks requiring language comprehension: although type 10 contains two full sentences, neither of them contains a filler gar dependency. In this respect accounts that include both structural complexity and resource restriction (Grillo's 2008 Generalized Minimality being an example) seem to be the most suitable approach to account for these data.

A possible limitation of our study might concern the classification of the participants in the two groups. In absence of specific quantitative tools to evaluate agrammatism in Italian, participants were classified as agrammatic or non-agrammatic according to clinical standard criteria (Luzzatti et al., 1994). However, the assessment of spontaneous speech was made by expert neuropsychologists and speech-language pathologists not involved in this study and was not based on the linguistic structures contained in the 'Comprendo' battery, avoiding any circularity between initial diagnosis and experimental results.

In summary, our results confirm a significant interaction between agrammatism and the comprehension of passive sentences, establishing that passives are the most sensitive detector for agrammatism. On the other hand, comprehension deficits with sentence coordination can be mostly imputed to the reduction of pSTM resources. Finally, difficulties in the processing of object relatives and center embedding seem to be determined both by structural and resource-based factors, pSTM being critical.

6. FUNDING

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