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Research Article

Relationships between working memory and the ability to repeat sentences in Alzheimer's disease

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Abstracts

The goal of this study is to assess the relationships between working memory and the ability to repeat sentences exhibiting different levels of syntactic complexity in Alzheimer's patients. Although syntax is considered to be relatively preserved at least in the first stages of the disease, sentences undergo simplification, which is attributed to patients' decline in working memory capacity. Working memory plays a central role in language processing and more crucially for the processing of complex sentences. Three complexity factors are manipulated in the current experiment: word order (canonical or not), type of branching (left or right branching), subordination (absence or presence of subordination). Thirty-five patients with Alzheimer's disease as well as a group of 16 controls matched for age, sex and education level participated in the study. They underwent sentence repetition testing as well as forward and backward digit span tasks. Sentences were strictly controlled for length (in terms of number of words and syllables), and for word frequency and Age of Acquisition (AoA). Our findings show that patients repeat significantly fewer sentences than controls, and that memory spans are correlated to sentence repetition scores for AD patients only. A regression analysis was carried out and the 3 above-mentioned complexity factors were shown to explain patients' scores.

Keywords: working memory, syntactic complexity, Alzheimer's disease, sentence repetition

Introduction

Alzheimer's disease (henceforth AD) is associated with a number of cognitive deficits among which memory deficit, involving both long term and working memory, plays a major role. Long term memory deficits encompass impairments in the ability to learn new information, a slower access to semantic memory [1-11] as well as impaired episodic memory [13,14-20]. Working memory is also affected [3,21-40], especially the central executive [41-48].

Language is also affected by AD. Language deficits are heterogeneous as the different linguistic domains (phonetics, lexicon, syntax ...) are not equally affected depending on the severity of the disease. It is generally accepted that AD primarily affects lexico-semantic aspects of language (Shuttleworth & Huber, 1988; Whatmough et al., 2003). By contrast, grammatical aspects are considered to be relatively intact, as the patient's oral production does not generally exhibit agrammatism, at least until severe stages of the disease are reached [32,42,34,31]. For instance, MCI individuals' language does not show a reduction of syntactic complexity [49-55].

Nevertheless, a detailed examination of patients' syntax compared to controls' reveals that syntactic simplifications can be observed even at the early stages of the disease. Patients with AD produce shorter sentences with fewer propositions and these simplifications tend to increase as the disease progresses [22,27,39, 5]. Other studies argue against the presumed preservation of morpho-syntactic features of language in AD. For instance, Sajjadi et al. findings show that the frequency of elliptical, abandoned and complex sentences show a degree of syntactic and grammatical impairment in mild AD patients. Fraser et al. [18] underline a considerable degree of heterogeneity in linguistic deficits in AD patients. Nevertheless, they observed a clear syntactic impairment in patients with AD, similar, although less severe, than the agrammatism seen in Broca's aphasia and progressive non-fluent aphasia.

Previous work on the comprehension of complex sentences also documented a decline in both normal and pathological aging. For instance, a reduced comprehension of passive sentences was observed in elderly adults. Research on patients with AD also documented comprehension impairments in various languages. Using the TROG (Test for the reception of grammar, Bishop, 1989) [9] assessing a variety of syntactic structures, Croot et al. =[12] found that the AD patients were more impaired on two-proposition sentences with non-canonical word order than on two proposition sentences with canonical word order. Moreover, they found that sentence comprehension deficits may arise in the earliest stages of AD. At the early stage of the disease, approximately 20 to 30% of patients showed deficits, while at the moderate stage almost all patients were impaired. Center-embedded Object relative clauses [44,41], or sentences containing multiple propositions (Waters, Caplan & Rochon, 1995) are particularly impaired.

It is generally assumed that the reduction of syntactic complexity is the consequence of working memory reduction in normal and pathological aging. Analyzing speech samples produced by young and older adults, Kemper & Summer [33] found that grammatical complexity was related to the measures of working memory including digit span and reading span. This suggested that working memory imposes limits on how many hierarchical relations can be formulated at one time, as embedded or subordinate clauses increase the burden on working memory. Similarly, Almor, Kempler, MacDonald, Andersen & Tyler [1] show that AD patients produce an increased proportion of pronouns compared to controls, and they argue that reduced working memory capacity is linked to this abnormal pronoun production, as a significant correlation has been found between the proportion of pronouns and working memory scores.

Some syntactic structures are known to be especially difficult to process. Typically, three complexity factors have been found to affect the ease with which a sentence is understood (or produced): (i) non-canonical word order, (ii) type of branching, and (iii) subordination. Non-canonical word order sentences include Object relative clauses (example 1) which have been shown to be more difficult to process than canonical Subject relative clauses (example 2). Moreover, left-branching relative clauses (examples 1 and 2) are more difficult to process than their right-branching counterparts (example 3). Left-branching relative clauses interrupt the matrix clause whereas no such interruption occurs in the case of right-branching.

(1) Left-branching Object relative clause: the man [that the woman is looking at] is talking to the child

(2) Left-branching Subject relative clause: the man [who is looking at the woman] is talking to the child

(3) Right-branching Object relative clause: the child is talking to the man [that the woman is looking at]

A large body of literature has evidenced that left-branching Object relative clauses are more difficult to process: they show longer reaction times, longer reading times, and more frequent comprehension errors (Holmes 1986, Hakes, Evans & Brannon 1976, [21] Larkin & Burns 1977,[38] Wanner & Maratsos 1978, Holmes & O'Reagan 1981, Ford 1983, [17] Waters, Caplan & Hildebrandt 1987, Gouvea & Poeppel 2000[20]; Just, Carpenter, Keller & Eddy 1996 [29] ; Stromswold, Caplan, Alpert & Rauch 1996).

A common assumption is that working memory capacity accounts for these findings. Verbal short term memory (typically assessed via forward digit spans and non-word repetition) corresponds to the temporal storage of information. Working memory (typically measured via backward spans or reading Span (Daneman & Carpenter, 1980) [16] additionally involves the central executive (Papagno & Cechetto (2019) [52]. Hence, the Capacity theory (King & Just 1991, [36] Just & Carpenter 1992) has sought to establish a causal relationship between working memory and the processing of complex sentences. Indeed, sentence comprehension involves a progressive integration of words in order to build a mental representation. Syntactic processing transforms a linear sequence of words into a nonlinear syntactic structure. This mental operation requires the temporary storage of word representations and of intermediate syntactic representations. Hence, the greater the distance between two elements which are linked together, the higher the probability of error, and the longer the duration of the integration processes (Gibson 1998).[19] In addition to working memory, the role of the phonological loop (STM) in sentence comprehension has also been investigated. Some patients with STM deficits have been shown to be able to perform normally on sentences requiring full syntactic analysis for their comprehension (e.g. Vallar & Baddeley, 1984). Nevertheless, Papagno and Cechetto (2019) suggest that syntactic comprehension is impaired in STM patients if they are tested with syntactic structures that are known to introduce a serious memory load (especially left-branching).

Most studies exploring the complexity of relative clause processing focus on comprehension while the present study concerns language production. However, according to Gibson (1998:52), the factors accounting for the difficulty of processing certain structures in comprehension also apply in production. Indeed, during sentence production, the speaker builds a mental representation of the message to be conveyed, and this mental representation has to be turned into a linguistic sequence, in other words, linearized. As in comprehension, this operation necessitates the temporary storage of the yet unprocessed elements in working memory. Nevertheless, previous studies failed to show a relationship between complex sentence production and working memory (Daneman & Green, 1986) [15]. For instance, although Reading Span strongly correlates with comprehension performances, it does not correlate with production performances (Daneman & Carpenter, 1980), which suggests that phonological memory is involved in neither sentence planning nor production. Similarly, Bock (1982) [6,10] and Levelt (1989) [40] propose that in production, lexical retrieval and syntactic planning are automated and can be processed online. In sum, Previous studies investigating the relationships between working memory and production of complex structures have not provided reliable evidence that these two processes either interact or are causally linked, contrary to what is found for language comprehension. A possible explanation is that language planning in spontaneous production involves choices at different levels (conceptual, syntactic and lexical), which are difficult to control for experimentally. As a result, the absence of a given structure in a subject's production does not necessarily mean that the subject is unable to produce this structure. For this reason, more constrained tasks are required in order to be able to assess the subjects's capacity to produce complex syntax. Altmann (2004) [2] used a constrained sentence production task in order to examine the speech of older adults with and without probable Alzheimer's disease. The participants were required to create a sentence that included two nouns and a verb. The stimuli were designed to elicit the production of passive sentences by manipulating the verb type and the order and animacy of nouns. Their findings show that individuals with AD, who are typically described as having preserved sentence production, were impaired when they were required to use words chosen by an outside source. Another more constrained method is the sentence repetition task.

Such a task necessarily involves short term memory, which "is a core factor of language repetition, especially when reproducing multiple or unfamiliar stimuli" (Majerus, 2013: 357) [43]. The sentence repetition task is widely used to assess children's grammatical development. Whether this task is a production task, a comprehension task or both remains unclear but it has proven to be a reliable tool to assess structural aspects of language (Miller & Chapman, 1981) [47]. This task has also been shown to be useful for assessing the language of patients with traumatic brain injuries (Meyers et al., 2001) [46]. A few studies have shown that this technique is also appropriate in assessing grammatical abilities in patients with AD. Indeed, articulatory capacities are well preserved in AD (Small et al. 2000), as suggested by echolalic behaviors in severe stages of the disease. Echolalia has also been interpreted as a sign of the preservation of some syntactic abilities (Bayles, 1984; Cummings et al. 1985) [13] Another advantage of the sentence repetition task is that it reduces the demands that are irrelevant to syntactic processing (such as lexical access). In addition, this task involves more than simple short term memory mechanisms: imitation is not a passive copy but a reconstruction of the stimulus (McDaniel & McKee, 1998) [45]. Indeed, it has been argued that being able to imitate a sentence structure correctly requires this structure to be part of the subject's grammatical competence. A longitudinal study by Holland et al. (1986) [24] showed that sentence repetition performances are well preserved in individuals with AD, although they decline as the disease progresses. Other studies showed that patients with AD had better repetition scores with meaningful short (6 words) sentences compared to meaningless long (9 words) sentences (Bayles & Tomoeda, 1996) [7]. Beales et al. (2019) [8] investigated sentence repetition performances in individuals with different dementia syndromes as well as their relationship with working memory. Based on the classification of errors provided by Hohlbaum et al. (2018) [23] , they found that the most typical error for AD participants was endings omission, suggesting that once the required storage for sentence processing exceeds the limits of the fixed capacity of working memory, the patients fail to repeat the stimuli.

Turning to syntactic complexity, Small et al. (2000) manipulated 3 complexity factors in their sentence repetition experiment: (i) canonical word order, (ii) right- or left-branching, and (iii) subordination, resulting in 6 types of sentential structures: active, passive, left-branching Object relative clause, rightbranching Object relative clause, left-branching Subject relative clause and right-branching Subject relative clause. In addition, short term and working memory scores were collected. They found that their mild to moderate AD patients had trouble with canonical sentences that were left-branching, and with rightbranching sentences that were non-canonical. The authors attributed this poor performance to the intervening clause between the subject and the verb of the matrix clause in the former case, and to the noncanonical thematic role assignment in the latter case, which placed a burden on working memory. Indeed, the significant correlations between sentence repetition and working memory scores indicated that both draw upon a common pool of activation resources. However, some other findings were unexpected as left branching Object relative clause (combining both embedding and canonicity as complexity factors) were not more difficult to process by individuals with AD. Another intriguing finding is that AD participants performed much better on passive sentences (non-canonical word order) than in active sentences. Finally, in contradiction with previous work (Caplan and Waters, 1999) they found that Subordination did not play a significant role in sentence repetition. However, in our view, Small et al.'s experimental material contains several possible confounding variables. First, the passive sentences were shorter than the other types of sentences (7 words vs. 9/10 words), which might explain why they were easy to repeat, as sentence length has been shown to influence the ease with which patients successfully repeat sentences (Bayles et Tomoeda, 1996). Second, word frequency was not uniform across conditions, which could be problematic as lexicalsemantic processing is compromised in AD. Finally, the subordinate sentences were always relative clause, so an effect of subordination cannot be disentangled from relativization. Therefore, these results are difficult to interpret and they suggest that the experimental sentences should be strictly controlled for in order to disentangle the complexity factors that influence repetition performances.

The goal of the present study is to investigate the ability to repeat sentences exhibiting different levels of syntactic complexity, and its relation to working memory capacity in individuals with Alzheimer's disease. Contrary to previous work, we carefully controlled for sentence length, word frequency and Age of Acquisition as well as subordination in order to avoid possible confounding variables.

We hypothesize that patients with AD should obtain lower repetition scores and working memory scores compared to controls, and that complex sent

ences should be the most difficult to repeat. Moreover, the three complexity factors (canonicity of word order, branching direction, subordination) should influence the participants' performance. Indeed, the non-canonical sentences, with a left subordinated clause should be the most difficult for AD patients. Finally, we predict that repetition scores should correlate with short term and working memory scores.

Materials and Methods

Participants

This study included 35 (10 men and 25 women) AD patients and 16 elderly controls (3 men and 13 women) matched for age and sociocultural background. All participants were monolingual French native speakers and had no reported hearing impairment. Patients met the NINCDS–ADRDA clinical criteria for a diagnosis of probable dementia of the Alzheimer type. The control participants with an MMSE score below 27 were not included in the study. In the AD group, the MMSE was used to split participants into four severity groups, following Kalafat et al. (2003)' [30] s recommendations (MMSE score between 20-25 = mild AD; 16-19 = moderate AD; 10-15 = moderately severe AD; 3-9 = severe AD). The participants were matched for age sex, and SES following Kalafat et al. (2003)'s criteria. Table 1 shows the participants' characteristics (Table 1).

Table 1: Participants' characteristics.

	n	SES	MMSE (min-max)	Age (min-max)
Controls	16	2.24	27.9 (27-30)	84.5 (79-95)
Mild AD	9	2.79	22 (20-25)	86.8 (75-95)
Moderate AD	8	2.47	17.8 (16-19)	86.5 (74-91)
Moderately severe AD	8	2.05	11.4 (10-15)	85.1 (71-95)
Severe AD	10	2.3	6.7 (1-9)	83.9 (73-93)

Tasks

In order to evaluate the relationships between syntax and memory on the one hand, and cognitive state on the other hand, participants were asked to perform three tasks: MMSE, memory spans and sentence repetition.

Stimuli in the sentence repetition task

The task was composed of 24 audio-recorded sentences with a male voice. All the sentences were controlled for length (number of words and syllables), word frequency (Lexique 3.8, New, Pallier, Ferrand, Matos, 2001)[50] and word age of acquisition (AoA) (IFDC, Kern & Gayraud, 2010). [35] Using only high frequency words and early AoA words was aimed to diminish the processing load of the lexico-semantic aspects of the sentences. The sentences were created according to three main syntactic criteria (word order, type of branching and subordination), resulting in eight sentence types as shown in Table 2.

These 8 different sentence types present different degrees of complexity related to the three abovementioned complexity factors as shown in Table 3.

Table 2: Sentence repetition categories.

Sentence type	Example
Simple	Le petit chat noir et blanc boit le lait de la ferme. The small black and white cat drinks the milk from the farm.
Passive	La lourde fenêtre de la chambre bleue est fermée par la maman. The heavy window of the blue bedroom is closed by the mom.
Complement	Le monsieur chante que le clown porte un gros nez rouge. The man sings that the clown is wearing a big red nose.
Relative:	
o Right-branching Subject	La fille mange le fromage sec qui est coupé sur la table. The girl eats the dry cheese which is cut up on the table.
o Right-branching Object	La fille ouvre la boîte que la dame cache dans sa chambre. The girl is opening the box which the lady hides in her bedroom.
o Left-branching Object	Dans le magasin, la couverture que le garçon lave est très douce. In the store the blanket which the boy is washing is very soft.
o Left-branching Subject	À l'école, la fille qui a des bottes dessine un poisson. At school the girl who is wearing boots is drawing a fish.
Interrogative	Qui le gentil docteur aide-t-il à bien dormir ce soir? Who is the kind doctor helping to sleep well tonigt?

Table 3: Sentence complexity factors.

	Word Order		Subordination		Type Branching		Complexity Score
Sentence types	**Cano**	**Non cano**	**Sub**	**Non sub**	**Left**	**Right**	
Simple	✓			✓			0
Passive		✓**1**		✓			1
Complement	✓		✓				1
Interrogative		✓		✓			1
Oject Subject Relative	✓		✓			✓	1
Object Object Relative		✓	✓			✓	2
Subject Object Relative		✓	✓		✓		3
Subject Subject Relative	✓		✓		✓		2

Simple, passive, complement, right and left branching subject relative sentences display a canonical word order (hence easier to process), while passive, left and right branching object relatives as well as interrogative sentences have a non-canonical word order (more difficult to process). Turning to Subordination, simple, passive and interrogative sentences are not subordinate (hence easier to process), while complement and all the relative clauses are subordinate (assumed to be more difficult to process). Finally, the type of branching concerns relative clauses only, right branching relative clauses are assumed to be easier to process while left branching relative clauses are assumed to be more difficult to process. Sentences totalizing a complexity scores of 2 or 3 were considered complex sentences.

Memory span tasks

All participants were asked to perform a forward and backward digit span task to assess their memory capacity (Wechsler, 1987). Digits were read by the researcher at a rate of one per second. For the forward span, participants were asked to repeat exactly the digits they heard. The backward span requires participants to repeat the digits in the reverse order. At each trial, a digit was added, until a maximum of nine was reached. If a mistake was made, participants were allowed two attempts. If the retest was wrong, then the maximal span was considered as the participant's span; if correct, then testing continued until two consecutive mistakes were made, or until nine digits were reached.

Procedure

The participants were tested in nursing homes in a face-to-face interview. Written informed consent was obtained from the participants and, where appropriate, their next of kin.

All participants were asked to repeat the 24 audio-recorded French sentences. They could listen as many times as they wished, although only the first attempt was taken into account. Prior to the task, two training sentences were proposed to test participants' hearing and to ensure that they understood what was required.

Analyses and Results

Considering the small number of AD and control participants, analyses were conducted using Linear Mixed Effects models. We used R (R Core Team, 2020) [54], lme4 (Bates, Maechler & Bolker, 2015) [4] to perform a linear mixed effects analysis of the relationship between sentence repetition and AD. We also used lmerTest library (Kuznetsova, Brockhoff, Christensen, 2017) [37] which allowed to obtain direct p-values. As fixed effects, we entered the different groups (control, mild AD, moderate AD, moderately severe AD, severe AD) and type of sentences (simple, passive, complement, interrogative, object-subject relative, object-object relative, subject-object relative, subject-subject relative), with interaction term, into the model. As random effects, we had intercepts for subjects and sentences. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality (Winter, 2013). The data entered into the model were not means but individual trials, which represented a large amount of data per group. This method has an additional advantage regarding the inclusion of random effects. Indeed, the sentences we created could be not free of bias. Including sentences as random effects ensures better surfacing. Furthermore, the existing random variation between groups and participants is therefore taken into account. Finally, the power of linear mixed effects models is well established (Pinheiro & Bates, 2000[53]; Oberg & Mahoney, 2007) [51].

Each participant obtained a sentence repetition score and two memory scores: one for the forward span and another one for the backward span. This constituted the analyses material.

Sentence repetition scores

It has been hypothesized that AD participants would score below the controls in a sentence repetition task, and that the scores would depend on the dementia stage. Overall, analyses have been first conducted to answer this question, then a model was run to investigate which grammatical criterion was the most influential on syntactic processing.

The 24 answers by subject were entered in a linear mixed effects model with repeated measures, where participants and the 24 sentences were settled as random effects whereas scores for the eight types of syntactic construction (grouped into two categories - simple vs complex) and the groups (as a function of their MMSE's scores) were the fixed effects. The results are illustrated in figure 1.

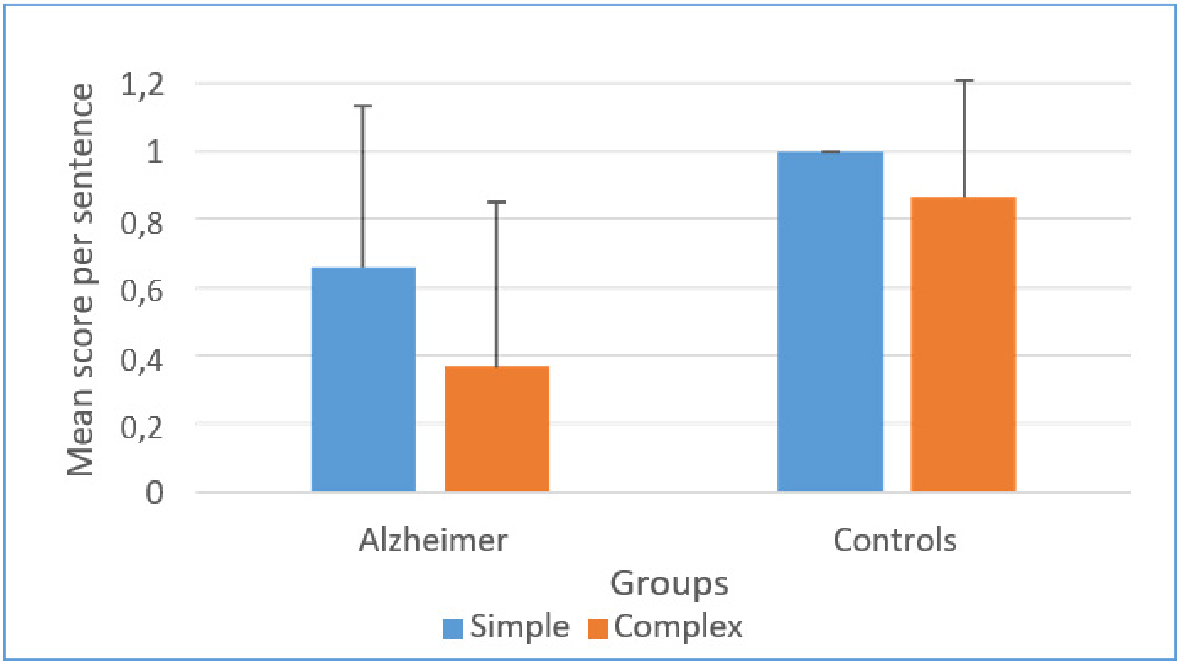

Figure 1: Simple and complex sentence repetition scores for AD and control groups.

Mean scores for the 24 sentences repetition per groups, are illustrated in figure 2 and the percentage of correct answers according to syntactic complexity are given in figure 3. The model indicated that the AD patients and the controls did not have the same scores in sentence repetition depending on the dementia stage. The model gave a group effect (F(1, 57.11) = 28.2, p<.0001), showing that the AD group successfully repeated fewer sentences than the controls. A syntactic complexity effect was also significant (F=(1, 25.38) = 7.23, p=.01), showing that the simple sentences were repeated more successfully than the complex sentences for all groups, and a significant interaction (F(1, 1085.35) = 5.87, p=.01) was found, showing that the scores decreased as a function of dementia and syntactic complexity. Moreover, despite the different results for the controls between simple and complex sentences, post hoc analyses using the least-squares means for the groups*syntactic complexity combinations indicated that controls did not perform lower when sentences were complex than when they were simple (p=.44), whereas the AD scores were lower for complex sentences than for simple sentences (p=.007) (Figure 2 &3).

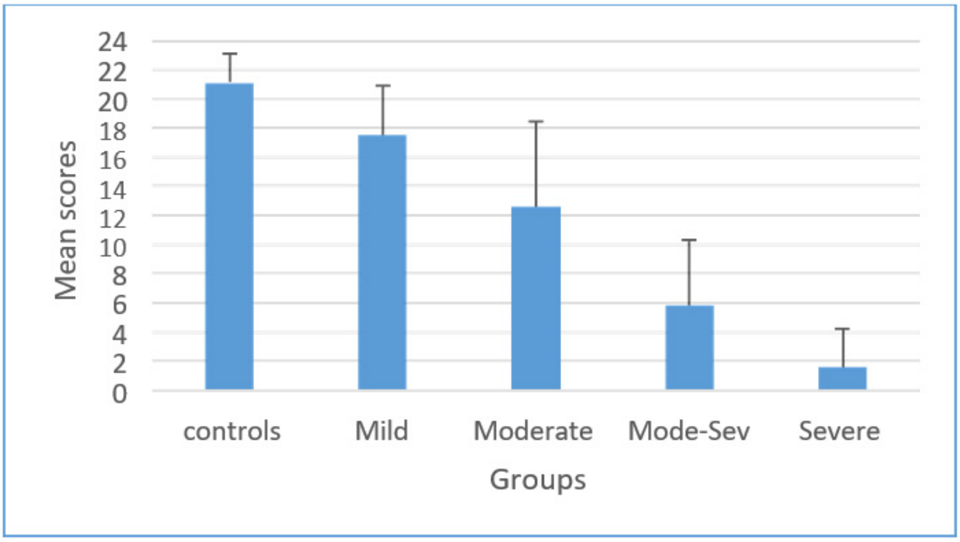

Figure 2: Mean scores for the 24 sentences repetition per group.

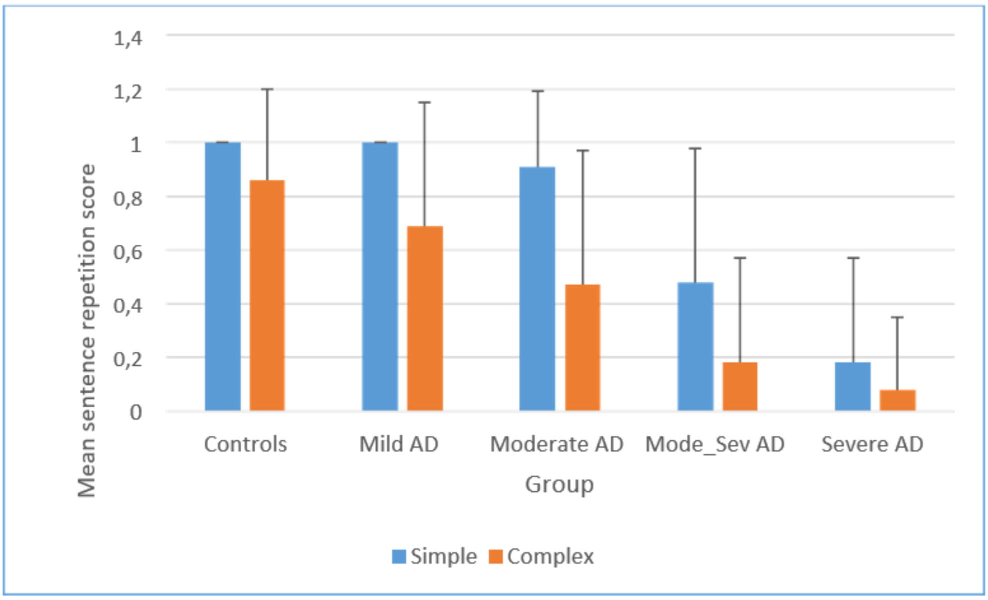

Figure 3: Mean sentence repetition scores per group, according to sentence complexity.

Designs considering the control group and the AD subgroups resulted in a similar pattern. The model gave a group effect ($F(4, 80.07) = 39.89$; $p<.0001$), a complexity effect ($F(1, 25.06) = 10.44$; $p=.003$) and an interaction ($F(4, 1081.13) = 3.78$; $p=.005$). A post-hoc analysis showed that the controls obtained significantly better scores compared to all groups except the mild AD group. There was no significant difference between the mild AD group the moderate AD groups, who were different from the moderately severe AD group. The severe AD participants differed significantly from all the other groups. The mild AD patients were indistinguishable from the controls and it would be interesting to investigate whether this is true for both simple and complex sentences, as illustrated in Figure 3. A post-hoc analysis indicated that their repetition scores for simple and complex sentences were very close to each other with a p-value equal to 1 for the simple and to .2 for the complex sentences. As for the overall results, for complex sentence repetition, the moderate, the moderately severe and the severe AD groups differed from the controls. A linear mixed effects model in which the repetition scores were entered as the dependent variable and subordination, branching place, canonicity and groups were the independent variables, was run to investigate which variable could account for the total scores. Moreover, the model calculated the interaction between groups and the three complexity criterions.

The model gave a significant effect for branching place ($F(2, 29.16)=6.04$; $p=.006$), for subordination ($F(1,30.84)=26.58$; $p<.0001$), for word order ($F(1, 26.29)=6.46$; $p=.02$) and for group ($F(4, 68.71)=47.72$; $p=.0001$), as well as a significant interaction between groups and branching place ($F(8, 1070.35)=5.15$; $p<.0001$) and groups and subordination ($F(4, 1069.74)=10.01$; $p<.0001$). A post-hoc analysis indicated that when sentences had no subordinate clause, the control group performed better than the moderately severe and the severe groups only (as shown in Figure 4), whereas, controls repeated better than all the AD groups with a left-branching clause (Mild AD: $p=.02$; Moderate, moderately-severe and severe AD: $p<.0001$) (Figure 4).

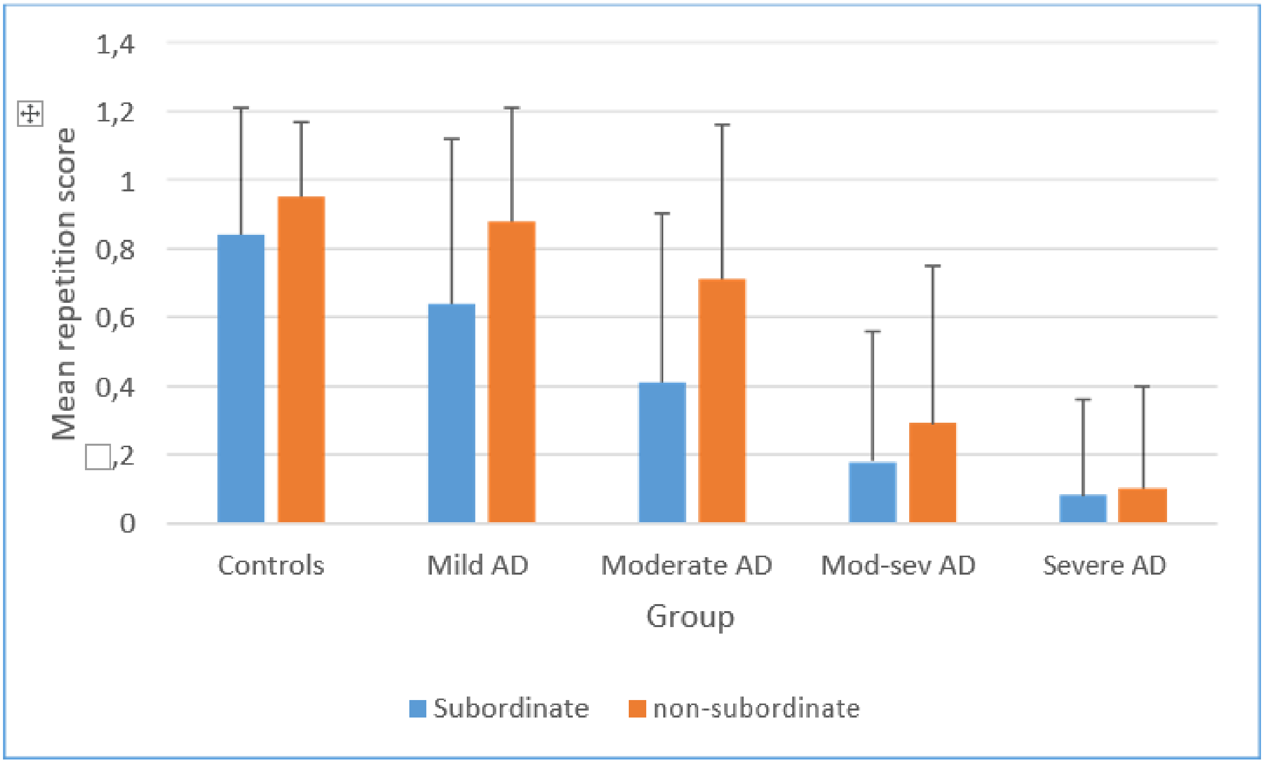

Figure 4: Mean scores and standard deviations for subordinate and non-subordinate sentences.

The control group performed better than all the AD groups, but the mild one, when the subordinate clause was left-embedded. Furthermore, the Tukey analysis showed that the controls repeated better the rightembedded clauses than the moderately-severe and the severe participants only. However, all the AD groups, but the mild AD, performed lower than the controls for the left-embedded sentences, as illustrated in Figure 5.

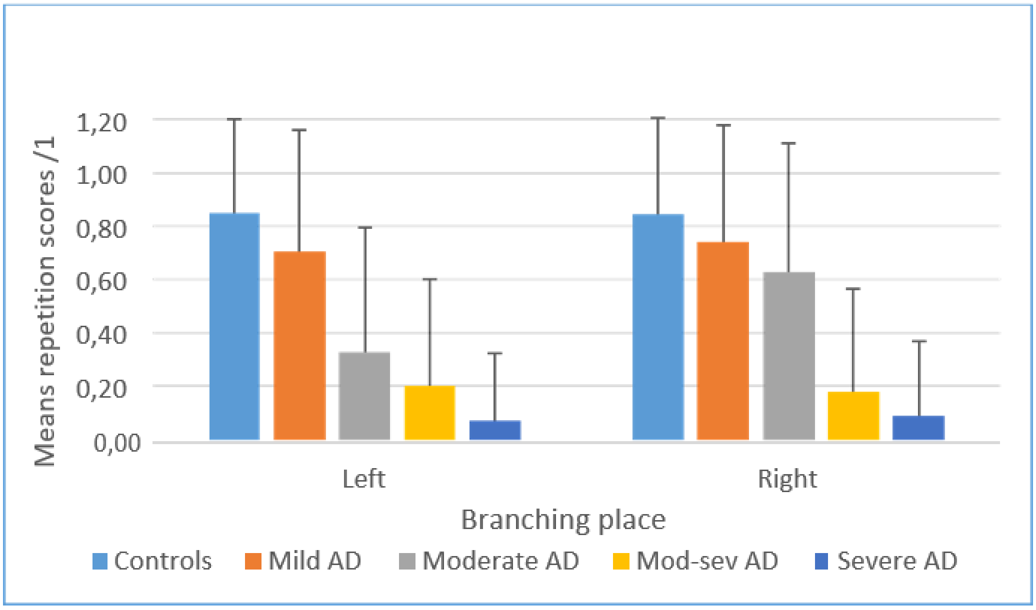

Figure 5: Mean repetition scores for left and right-branching sentences.

As illustrated in Figure 6, we observed an evolution of repetitions from quasi-identical intragroup performances for simple and complex sentences (except in the moderate AD group, p = 0,003), then to a drop in intragroup performances for complex sentences while maintaining capacities in simple sentences (moderate AD group), and finally to a general decline in sentence repetition (moderately severe and severe AD groups).

In the next sections, we investigate whether these declines and changes were memory related or not (Figure 4).

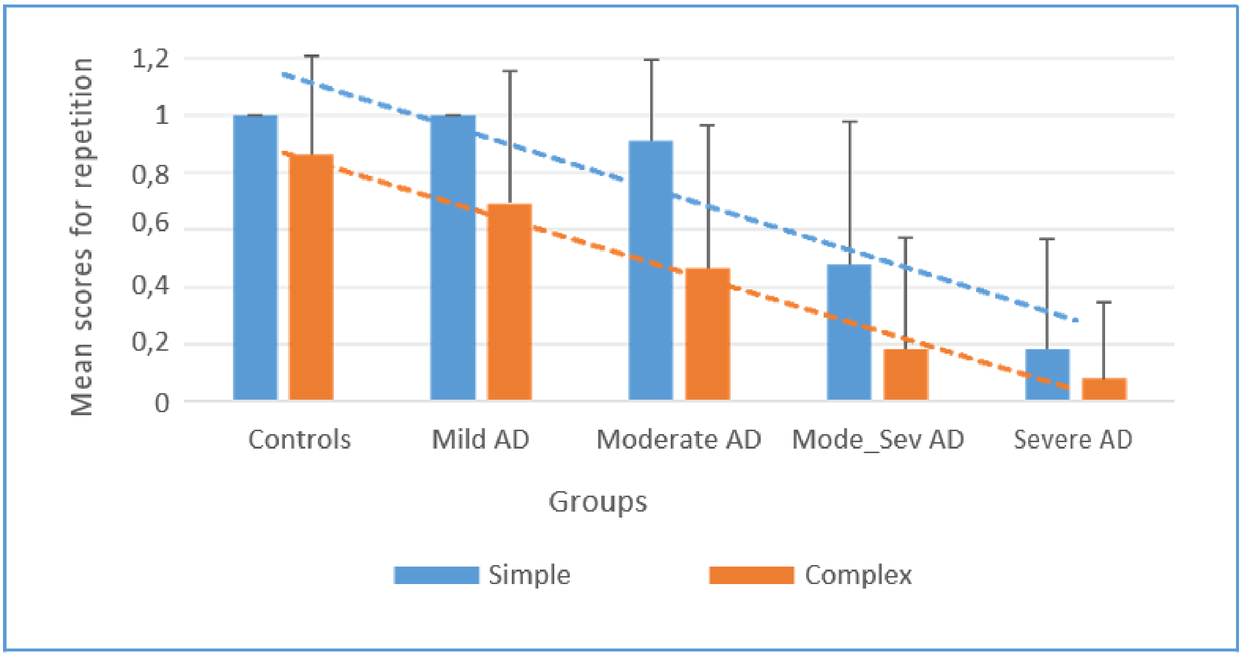

Figure 6: Mean simple and complex sentences repetition scores for control and AD subgroup.

Memory scores

Figure 7 shows the scores obtained by the participants in the forward and backward digit span tasks. Forward and backward spans were collected and put into a linear mixed effects model where span scores were the dependent variable, while groups (AD vs controls) and span types (or memory types (forward vs backward)) were the independent variables. Subjects have been settled as the random effect.

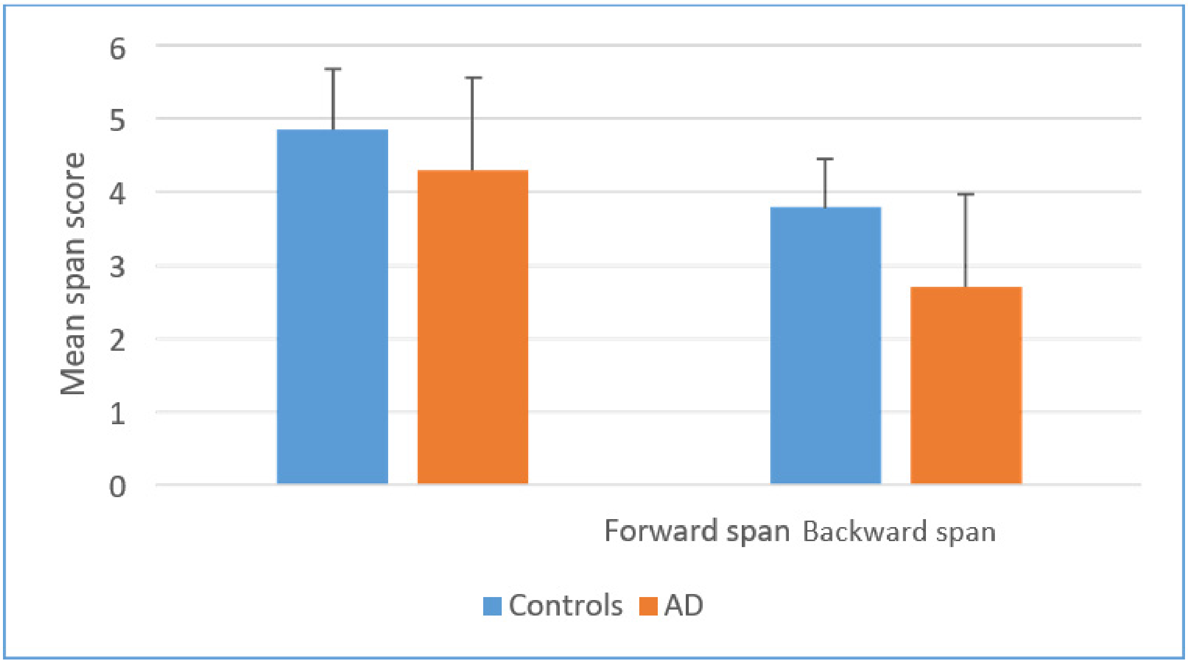

Figure 7: Mean forward and backward span scores for AD and control groups.

A linear mixed effects model showed a group effect (F(1, 38.92) = 6.09; p=.02), a span effect (F(1, 38.27) = 70.59; p<.0001) and the interaction tended to be significant (F(1, 38.27)=3.08; p=.08), indicating that memory decline tend to be both AD related and working memory related.

A post-hoc analysis showed that while, forward spans are not significant between AD and control groups (p=.44), it is significant between the two groups for backward spans (p<.0001). A deeper analysis examining the control group and the AD subgroups showed a group effect (F(4, 36.55)=14.43; p<.0001), and a span effect (F(1, 36.13)=86.3; p <.0001) but no interaction (F(4, 36.13)=1.51; p=.22). Subgroups' spans are illustrated in Figure 8.

Although a Tukey is not possible to run, figure 6 shows that memory performances appears to decline rapidly in the more severe stages of dementia. As syntax and memory have been shown to be in decline in AD as a function of dementia stage, we performed a correlation analysis in order to investigate the relationship between syntax and memory.

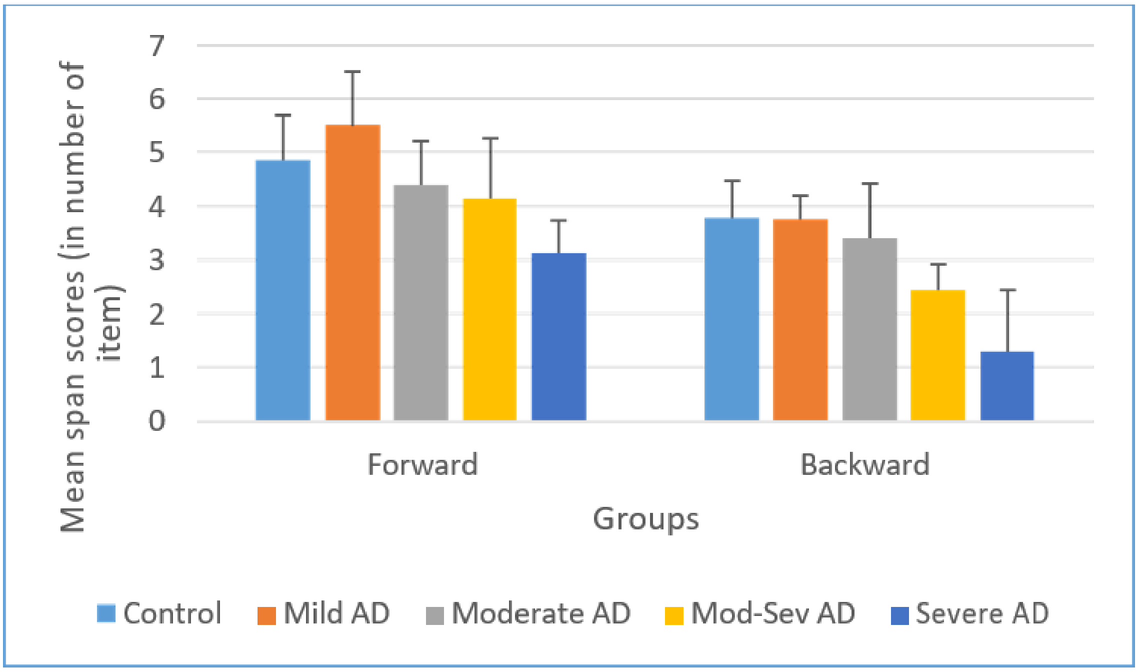

Figure 8: Mean backward and forward span scores for mild, moderate, moderately severe and severe AD vs Control group.

Correlations

A correlation analysis was conducted to investigate the link between memory and sentence complexity in a repetition task. This analysis focused on phonological memory (forward span) and working memory (backward span) on the one hand, and on the AD and controls' repetition scores for the three complexity factors – subordination, word order, branching place –, on the other hand.

In the AD group, the forward memory span was correlated with the three complexity factors: non-canonical word order (p=.0005), subordination (p<.0001) and right (p<.0001) or left branching (p=.004). Regarding the backward span in the AD groups, correlations were significant for non-canonical word order (p=.002), for subordination (p=.001), for right (p=.0003) and left-branching (p=.007) factors. The coefficients showed a stronger link between the subordinate and the right-embedded sentences for the two types of memories (see table 4).

Table 4: Correlation matrix between span scores and sentence complexity factors in the AD group2.

	Right	Forward	Backward	Left	Total	Non Cano	Sub
right	1,00	0,76***	0,66**	0,84***	0,95**	0,93***	0,94***
forward	0,76***	1,00	0,62**	0,56*	0,70***	0,65**	0,71***
backward	0,66**	0,62**	1,00	0,53*	0,64**	0,59*	0,62***
left	0,84***	0,56*	0,53*	1,00	0,94***	0,94***	0,95***
total	0,95***	0,70***	0,64*	0,94***	1,00	0,97***	0,99***
non cano	0,93***	0,65**	0,59*	0,94***	0,97***	1,00	0,96***
sub	0,94***	0,71***	0,62**	0,95***	0,99***	0,96***	1,00

Moreover, all the coefficients were positive, indicating that the better the memory, the better the results in repetition.

In the control group (Table 5), forward span was correlated with only right-branching scores (p=.04); backward span tended to be correlated with non-canonical word order (p=.06). The strongest coefficient for forward span was with non-canonical word order scores (.56) whereas the coefficient with leftbranching sentences was low (.09). Backward memory scores showed the highest coefficient with noncanonical word order scores (.52) but a low score with the subordination factor (.08) (table 5). Surprisingly, some negative coefficients were found between backward span scores and right-branching sentences on the one hand, and for forward span scores and subordination on the other hand (Table 5).

Table 5: Correlation matrix between span scores and sentence complexity factors in the control group.

	Right	Forward	Backward	Left	Total	Non Cano	Sub
right	1,00	0,26	-0,35	0,23	0,49	0,39	0,56*
forward	0,26	1,00	0,32	0,09	0,30	0,56*	-0,02
backward	-0,35	0,32	1,00	0,35	0,39	0,52.	0,08
left	0,23	0,09	0,35	1,00	0,81**	0,72*	0,84***
total	0,49	0,30	0,39	0,81	1,00	0,84**	0,89***
non cano	0,39	0,56*	0,52.	0,72*	0,84**	1,00	0,63*
sub	0,56*	-0,02	0,08	0,84***	0,89***	0,63*	1,00

Discussion

In this study, we investigated the relationship between syntactic complexity and working memory in individuals with AD via a sentence repetition task manipulating different factors of complexity: word order, subordination and place of branching.

In line with previous studies (Slegers et al., 2018) the AD participants' syntactic performances changed as a function of dementia stage. Indeed, performance in the sentence repetition task was lower for the AD participants than for the controls and this difference was gradual with the dementia scale. Although it is generally assumed that syntax is relatively preserved in AD, repetition scores showed a gradual decline. If the sentence repetition task indeed assesses a subject's syntactic capacities, then it can be claimed that AD is associated with a grammatical decline. As in Small, Kemper, & Lyons (2000), an effect of structural complexity was found. Indeed, the simple sentences were the easiest whereas the sentences with subordination or non-canonical order were more complex to repeat. The control group showed lower performances for the complex sentences too because they were also sensitive to sentence complexity. However, our results are also in partial contradiction with Small et al. (2000)'s study which found that some of the most complex sentences (remarkably passives) in their experiment were successfully repeated by AD patients. However as these sentences were also the shortest ones, this calls their results into question. Our findings suggest that sentence length was a methodological bias. Indeed, when this factor is controlled for, as in the current study, complex sentences are more difficult to repeat than simple sentences.

Previous studies showed a complexity effect for subordination, word order and type of branching [25,56-60].

resulting in increased processing time and number of errors. In the present study, the linear mixed effect model showed that syntactic complexity was due to a large degree to subordination: subordinate sentences seemed to be more difficult to process because of their higher demand on working memory. Canonicity played a role too, especially for AD participants, for whom canonical word order was easier to repeat than non-canonical word order. Finally, branching place was also important since the moderately severe AD group repeated better the right than the left-branching sentences. It is not surprising as left-branching sentences are known to be difficult to process even in people without cognitive impairment. It can be observed that the controls and mild AD patients repeated the leftbranching sentences as well as the right-branching ones, while the moderate AD patients had serious difficulties in repeating the left-branching sentences. Indeed, while their scores for the right-branching sentences remained almost identical to those of the controls and the patients with mild AD, their scores for the left-branching sentences were almost equal to those of the moderately severe and severe AD patients. A rapid decline in the ability to process left-branching sentences and a performance maintenance for the right-branching sentences was observed. However, more advanced stages of dementia showed a general decline in the repetition of the subordinate sentences, regardless of branching place. In view of the previous studies [26, 61-70] it can be noted that the leftbranching clauses add complexity to syntactic processing in the sense that interrupting the matrix clause requires more memory capacities (working memory) and therefore more cognitive resources than the right-branching sentences which present an expected order of sentential constituents. This could be explained by the Capacity Theory [28]: the resources necessary to maintain the matrix clause during the processing of the relative clause require resources in working memory. Indeed, for Papagno and Cechetto (2019), center-embedding is the key factor of syntactic complexity as they argue that passive sentences, as well as right-branching subject relative clauses, despite being syntactically more complex than active sentences, are not as demanding as center-embedded sentences in terms of memory load. However, in spite of this level of complexity, it appeared that the controls and mild AD patients were able to compensate for this difficulty, which was no longer the case with moderate AD sufferers. In the moderately severe and severe groups, even the supposedly easier rightbranching sentences exceeded the participants' capacity.

Syntax and working memory have been shown to be correlated in our study, indicating that the better the working memory, the better the syntax scores. Indeed, our analyses have shown that AD participants have lower working memory scores than controls. Here again, a more significant decline occurs in the most severe stages; thus, severe AD participants have lower forward and backward spans than mild AD participants. These results are in line with previous work who found a correlation between syntactic complexity and working memory (Kemper & Summer, 2001; Almor et al., 1999).

Working memory difficulty is greater for the AD patients than for the controls, and gets more important as a function of the dementia stage. The correlation analyzes indicated that working memory as well as short term memory are associated with syntactic processing in the AD groups, while almost no correlation was found in the control group. Indeed, Levelt (1989) claimed that lexical retrieval and syntactic planning are automated and thus do not tax working memory. However, in the case of AD, syntactic complexity increases the burden of processing which exceeds the limits of working memory (Kemper & Summer (2001). Another issue would be that working memory plays a role in controls' syntax but this is not noticeable because of the automated nature of the processes (Levelt, 1989). An alternative explanation is that this lack of correlation between memory and sentence processing in the control group could reflect the limited variance in performance within the control group. The correlations between sentence repetition scores and STM (forward digit spans) in the AD group but not in the control group can be explained by the fact that within the AD group, although STM scores were preserved in the mild and the moderate sub-groups, they showed a decline in the moderately severe and severe groups.

Conclusion

In conclusion, our study suggests that a sentence repetition task is a valuable tool to assess AD patients' grammatical capacities, provided that the sentence stimuli are rigorously controlled for, in particular in terms of sentence length. In addition, compared to spontaneous production analysis, this task permits to manipulate precise syntactic complexity factors, which is not possible with spontaneous speech. We observed a syntactic decline in AD by demonstrating lower repetition scores in a sentence repetition task, as a function of dementia stage and sentence complexity. Moreover, some complexity factors have been shown to play a crucial role: subordination impacts the participants' ability to perform the sentence repetition task to a large degree, as do branching type and canonicity to a lesser degree. Finally, working memory decline has been found in AD participants, and this decline was strongly correlated with their ability to repeat sentences.

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Conflict of interest

The authors declare no conflict of interest.

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