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ARTICLE

Relationship between working memory and complex syntax in children with Developmental Language Disorder

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Abstract

Some theories of Developmental Language Disorder (DLD) explain the linguistic deficits observed in terms of limitations in non-linguistic cognitive systems such as working memory. The goal of this research is to clarify the relationship between working memory and the processing of complex sentences by exploring the performance of 28 French-speaking children with DLD aged five to fourteen years and 48 typically developing children of the same age in memory and linguistic tasks. We identified predictive relationships between working memory and the comprehension and repetition of complex sentences in both groups. As for syntactic measures in spontaneous language, it is the complex spans that explain the major part of the variance in the control children. In children with DLD, however, simple spans are predictive of these syntactic measures. Our results thus reveal a robust relationship between working memory and syntactic complexity, with clinical implications for the treatment of children with DLD.

Keywords: working memory (WM); syntax; children; Developmental Language Disorder (DLD)

Introduction

Developmental Language Disorder

Developmental Language Disorder (DLD, previously Specific Language Impairment, SLI) is a developmental disorder which affects oral language acquisition. Children with DLD show severe and persistent language impairment, mainly in the areas of phonology and morphosyntax (Jakubowicz & Tuller, 2007). However, they develop normally without showing signs of neurological damage, sensorial disabilities (such as deafness), severe cognitive impairment, and pervasive developmental disorders (Leonard, 1998, 2014). The term 'specific', present in the previous label 'SLI', referred to the fact that the impairment was claimed to be restricted to language, with many authors having described various syntactic deficits (see for instance

Parisse & Maillart, 2004, or Jakubowicz & Tuller, 2007, for reviews with French-speaking children). The most frequently reported deficits are found in the processing of sentences that show a non-canonical ordering (involving what is called 'syntactic movement'), namely sentences which differ from the French/English canonical Subject–Verb–Object (SVO) word order. These deficits have been observed for different structures which all require syntactic movement and the building of a long-distance syntactic dependency: passive clauses (Marinis & Saddy, 2013; Montgomery & Evans, 2009; van der Lely, 1996), accusative clitics (Paradis, Crago, & Genesee, 2003; Tuller, Delage, Monjauze, Piller, & Barthez, 2011), object relatives (Adani, Forgiarini, Guasti, & van der Lely, 2014; Contemori & Garraffa, 2010; Friedmann & Novogrodsky, 2004), and object questions (Jakubowicz, 2011; Marinis & van der Lely, 2007; van der Lely, Jones, & Marshall, 2011). Children and adolescents with DLD were also observed to produce embedded clauses relatively infrequently (Prévost, 2009; Tuller, Henry, Sizaret, & Bathez, 2012; Zebib, Tuller, Prévost, & Morin, 2013). This tendency differentiates their language profile from that of L2 children who display a proportion of embedded clauses similar to that of typically developing L1 children in spontaneous language (Scheidnes & Tuller, 2013).

The existence of such language impairment, in the presence of an intact general cognitive system, was taken to suggest that the narrowly defined language faculty is quite independent of the other cognitive systems (van der Lely & Marshall, 2011). However, certain researchers have questioned the existence of a deficit strictly limited to language in children with DLD, claiming that these children rather show numerous deficits in other non-linguistic domains, such as general low-level problems with auditory temporal processing (Tallal, 1976) or other non-language impairments such as motor disorders and executive impairments (Bishop, Snowling, Thompson, Greenhalgh, & CATALISE consortium, 2016). More generally, numerous findings reported lower-than-expected performance on non-verbal cognition in school-aged children and adolescents with DLD (see Tomblin & Nippold, 2014). This is precisely one of the reasons for which the label 'Specific Language Impairment' has been replaced by 'Developmental Language Disorder' (Bishop *et al.*, 2016). Ullman and Pierpont (2005) assert, for example, that most individuals with DLD show an abnormal development of brain structures affecting the procedural learning system (i.e., 'Procedural Deficit Hypothesis'). This development leads to non-language impairments in motor skills, temporal processing, and working memory (WM). WM deficits are well known in DLD, particularly the persistent difficulties in non-word repetition which are considered to be clinical markers of DLD (e.g., Gathercole & Baddeley, 1990; Graf, Evans, & Else-Quest, 2007; Montgomery, 2002; or for French: Thordardottir *et al.*, 2011). Other deficits have been identified through measures of digit and word spans (e.g., Archibald & Gathercole, 2006; Durrleman & Delage, 2016; Hick, Botting, & Conti-Ramsden, 2005) as well through complex-span tasks assessed by dual-processing paradigms (e.g., Archibald & Gathercole, 2007; Ellis Weismer, Evans, & Hesketh, 1999; Hoffman & Gillam, 2004; Lukács, Ladányi, Fazekas, & Kemény, 2016; McDonald, Seidel, Hammarrlund, & Oetting, 2018; Montgomery, 2000). For Archibald and Gathercole (2006), these various deficits are substantial and generally co-occur in children with DLD, whereas visual WM appears to be less commonly affected.[1] In a

[1]Note that Vugs, Hendriks, Cuperus, Knoors, and Verhoeven (2017) also underlined the relative preservation of visuospatial WM in children with DLD aged seven to eight.

more recent study, Archibald and Harder Griebeling (2016) suggest, however, that deficits displayed by children with DLD in complex-span tasks are due to their impairment in simple spans, notably in phonological storage. Indeed, they observed no difference between controls and children with DLD when the level of difficulty of the complex-span tasks was adjusted for each child's short-term memory storage capacity.

Working memory

"Working memory involves the temporary storage and manipulation of information that is assumed to be necessary for a wide range of complex cognitive activities" (Baddeley, 2003, p. 189). Although it remains a subject of debate (especially by supporters of the unitary view of working memory, such as Conway & Engle, 1994), Baddeley and Hitch's (1974) modular tripartite working memory model is recognized as the most influential memory model in psycholinguistics. This model contains an attentional control system, the 'central executive', which is aided by two subordinate systems: the 'phonological loop' which stores acoustic and verbal information and the 'visuospatial sketchpad' which stores visuospatial information. In 2000, a fourth component was added to the model, the 'episodic buffer', which functions as an interface between both subordinate systems and the activation of information stored in long-term memory; it is also controlled by the central executive which regularly retrieves information from this buffer.

The capacity of the phonological loop is most accurately assessed by SIMPLE-SPAN TASKS (Barrouillet & Camos, 2007). These tasks require the simple storage of verbal information (e.g., forward digit span, word and non-word repetition). The non-word repetition task appears to be the most frequently used in clinical practice as well as in research. It is considered to be "a relatively pure measure of the capacity of the component of the working memory system known as the phonological loop" (Hansson, Sahlén, & Mäki-Torkko, 2007, p. 310). Simple spans gradually improve with age, especially between two and nine years old, and reach adult levels by adolescence (Barouillet & Camos, 2007). The capacities of the central executive, associated with one of the two slave subsystems, are measured with the so-called COMPLEX-SPAN TASKS, which require storage and simultaneous processing such as reading sentences, counting collections, or even solving arithmetic operations (Barouillet & Camos, 2007). Backward digit span, listening span (Gaulin & Campbell, 1994), counting span (Case, Kurland, & Goldberg, 1982), and reading span (Daneman & Carpenter, 1980) belong to this category. In these complex-span tasks, additional processing demands are combined with the capacity of remembering a list of items (see Gathercole, Pickering, Ambridge, & Wearing, 2004; La Pointe & Engle, 1990; Turner & Engle, 1989). Performance improvement with age in complex spans seems to be more linear than in simple spans, which improve more rapidly initially but then level off at about the age of nine (Barrouillet & Camos, 2007; Siegel, 1994). Indeed, using the backward digit span, listening span, and counting span, Gathercole *et al.* (2004) observed that the increase in these complex-span tasks is linear in children aged six to fourteen years and then stabilizes later, between the age of fourteen and fifteen years. This lengthy development of complex spans until the end of adolescence can be linked to late cerebral maturation, especially of regions within the frontal lobes which are involved in planning and executive functions (Collette & van der Linden, 2002).

Working memory and syntax

As for the relationship between WM and language skills, many studies show a direct link between WM and lexical acquisition (see Gathercole, Service, Hitch, Adams, & Martin, 1999; Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, & van der Linden, 2006), and more recently a link between WM and syntactic development. In their study comparing word/non-word repetition and the production of complex sentences in spontaneous language samples, Adams and Gathercole (2000) confirm that children aged three to five with a more efficient phonological loop produced longer and more complex sentences than those with less efficient WMs. Similarly, Willis and Gathercole (2001) show that children aged four to five who displayed low phonological loop capacities (assessed via non-word repetition and forward digit span) repeated significantly fewer complex sentences compared to children showing better performance in the memory tasks. Furthermore, Poll, Miller, Mainela-Arnold, Adams, Misra, & Park (2013) found that performance in listening span predicts scores of six- to thirteen-year-old children in a standardized task of sentence repetition. In younger children, Dispaldro, Deevy, Altoé, Benelli, and Leonard (2011) also suggested that results in word repetition strongly predict grammatical abilities in children aged three to four, especially for clinical markers of DLD such as the mastery of accusative clitics.[2] For complex syntactic constructions, Bentea and Durrleman (2014) found that WM measures (assessed by forward and backward digit span) correlated with the comprehension of object *wh*-questions and relative clauses in five-year-olds. In older children (aged seven to nine), this link was limited to the most complex constructions involving intervention effects in the presence of two NPs, according to Rizzi's approach to Relativized Minimality (2002) such as "Show me **the lady**$_i$ that **the girl** is kissing t_i", as compared to simpler constructions like "Show me who$_i$ **the girl** is kissing t_i". Results obtained by Engel de Abreu, Gathercole, and Martin (2011) are of particular interest since these authors compared the role of simple and complex spans of five-year-old children in their general language abilities. They claimed that simple spans (assessed by forward digit span and non-word repetition) are specifically linked to lexical capacities in children, whereas complex spans (assessed by backward digit span and counting recall task) are strongly linked to syntactic comprehension.[3] More specifically on syntax, Montgomery, Magimairaj, and O'Malley (2008) compared the role of simple spans (assessed by non-word repetition) and complex spans (assessed by listening span) in the comprehension of simple and complex sentences in children aged six to twelve. These authors observed a positive correlation between the comprehension of complex sentences (including passives and pronominals/reflexives) and performance on complex spans. Moreover, regression analyses revealed that the complex spans results explain 30% of the variance in the comprehension of complex sentences. In contrast, the comprehension of simple sentences (with SVO constructions) did not correlate with any WM task.

As previously explained, verbal WM is clearly impaired in children with DLD. Among various theories suggesting the role of external factors in developing

[2]These personal pronouns lead to non-canonical structures in Romance languages (French or Italian, for instance) since the object is in a preverbal position, as demonstrated in the following example in French: "il *le* lave" 'he *him* washes'.

[3]Interestingly, Verhagen and Leseman (2016) found similar results in Dutch-speaking monolingual and bilingual children aged five: simple spans significantly predicted both vocabulary and grammar, whereas complex spans predicted only grammar.

language skills, Jakubowicz (2011) hypothesizes that these WM weaknesses limit the ability of individuals with DLD to process complex sentences, which explains their long-lasting immature level of grammar. This hypothesis seems to be supported by Montgomery and Evans (2009), who found in children with DLD (aged six to twelve) a positive correlation between WM (assessed by a complex-span task, an adaptation of a listening span task) and the comprehension of complex sentences, such as passives and structures containing object pronouns, that required the children to compute a non-local dependency. On the other hand, simple spans (assessed by non-word repetition) were correlated to simple (SVO) sentence comprehension.[4] Similarly, Frizelle and Fletcher (2015) examined the contribution of different WM tasks (including simple and complex spans) in the repetition of relative clauses in 35 children with DLD aged six to seven, compared to aged-matched TD children and to language-matched ones (aged four). They found that, for children with DLD, the ability to repeat the most complex relative clauses (i.e., the bi-clausal ones) was related to verbal complex spans, and more precisely to the listening span, which was not the case for simpler relative clauses. An example of such DUAL PROPOSITIONAL relatives would be, for an object condition, "The girl ate the sweets that you brought to the party", different from simpler PRESENTATIONAL relative clause constructions that express a single proposition such as "There is the picture that you drew on the wall last week". The same pattern was found in DLD children for the more difficult types of relative clauses such as object, oblique, and indirect object clause types. Their processing was correlated with performance on complex spans, whereas that of simpler structures (i.e., intransitive subject relatives) was related to simple spans. Such relationships were not found in control children in which verbal simple spans (digit recall) were associated with relative clauses, regardless of complexity. This suggests that children with DLD rely on complex WM (assessed by complex-span tasks) for repeating complex syntactic structures, whereas typically developing children only rely on passive verbal storage (assessed by simple-span tasks) to repeat sentences for which they have a sufficient syntactic knowledge. Still on the subject of DLD, Robertson and Joanisse (2010) evaluated spoken sentence comprehension, including subject and object relatives, in 14 English-speaking children with DLD (*M* age = 10;4) in a task in which difficulty increases with increasing working memory loads.[5] They found that children performed less accurately than age-matched controls in this task and that general performance decreased when memory load increased. Moreover, a significant correlation between non-word repetition and overall sentence comprehension was also reported in the most demanding memory-load conditions, suggesting that sentence comprehension was associated with simple storage capacity. Durrleman and Delage (2016) also found a significant positive correlation between the production of third person accusative clitics and WM measures, more precisely on backward digit span, in 22 individuals with DLD aged five to sixteen.

[4]Montgomery, Gillam, and Evans (2016) recently argued for a working memory-based account to explain these relationships, with WM limitations being directly associated with poor (simple and complex) sentence comprehension in DLD (see also Gillam, Montgomery, Gillam, & Evans, 2017, for an overview).

[5]Memory load was increased in a comprehension task using a picture selection task, with pictures appearing either from the onset of sentence presentation, immediately after the sentence, or three seconds after.

Interestingly, this correlation was obtained after controlling for non-verbal reasoning, thus supporting the existence of a specific relationship between complex syntax and complex working memory capacities. This perspective gains further empirical support from studies by Marinis and Saddy (2013) and Weismer, Davidson, Gangopadhyay, Sindberg, Roebuck, and Kaushanskaya (2017). The first set of authors indeed showed a correlation between the processing of passives and working memory abilities as measured by a listening recall task in 25 children with DLD (*M* age = 7). Still using a complex WM task (visual N-back), Weismer and colleagues (2017) found that WM performance predicts results in a grammatical judgment task, including omissions of verbal inflexions in complex sentences, in 30 children with language impairment (including participants with DLD and autism spectrum disorders; *M* age = 9;8). Finally, in a more recent study, Montgomery, Evans, Fargo, Schwartz, and Gillam (2018) found that complex working memory (assessed by two tasks involving concurrent processing and storage) mediates complex sentence comprehension (non-canonical sentences) in 117 children with DLD aged seven to eleven, whereas for canonical structures, these children seem to depend on long-term memory language knowledge.

Syntactic complexity

The studies reviewed above show that working memory capacity and the mastery of complex syntax are linked. Jakubowicz (2005, 2011; see also Jakubowicz & Strik, 2008) attempted to quantify this so-called 'complex syntax' by attributing a high degree of syntactic complexity to certain grammatical structures. More precisely, she assumes that the cognitive load involved in processing complex syntax depends on the number and nature of syntactic operations necessary for sentence processing (Jakubowicz, 2011; Jakubowicz & Tuller, 2007). Two main factors determining syntactic complexity were thus considered:

> *Syntactic movement*: the complexity of a sentence is related to the amount of disruption to the canonical structure (SVO): the more syntactic movement a structure undergoes, the more complex it is. Jakubowicz and Strik (2008; see also Jakubowicz, 2011) applied this reasoning to the production of object questions in French:[6] The less complex structures consist of questions where the object is produced in its *in situ* post-verbal position, without any movement (1), as compared to more complex structures like object questions containing the movement of the object (2), and to the most complex structures which are associated with subject–verb inversion[7] (3). All of these forms are grammatical in spoken French.

[6]Note that van der Lely and Batell (2003) also studied object questions in English to test their RDDR (Representational Deficit for Dependent Relations) account. They postulated that children with grammatical DLD had optional movement, which could explain why they sometimes produced appropriate movement operations in object questions and, on other occasions, demonstrated deficits in both WH-operator and Q-feature movements.

[7]Indeed, the possibility, in French, of proceeding to an inversion of subject–verb arguments leads to the most complex construction, containing two instances of movement, as in (3) for object questions and (4) for object relatives.

(1) tu pousses qui ?
'you push who?'
(2) qui tu pousses ?
'who you are pushing?'
(3) qui pousses-tu ?
'who are you pushing?'

This reasoning can also explain why object relative clauses with subject–verb inversion (4), which contain two instances of syntactic movement and result in a non-canonical word order (OVS), are more complex than object relative clauses without such subject–verb inversion (5) but that also result in a non-canonical word order (OSV). The latter, in turn, are more complex than subject relative clauses (6), which respect the canonical word order (SVO).

(4) Object relative with subject–verb inversion
Le garçon que rencontre Max au cinéma [OVS order]
'The boy that meets Max at the movies': the boy who/that Max meets
(5) Object relative without subject–verb inversion
Le garçon que Max rencontre au cinéma [OSV order]
'The boy that Max meets at the movies': the boy who/that Max meets
(6) Subject relative
Le garçon qui rencontre Max au cinéma [SVO order]
'The boy who meets Max at the movies': the boy who/that meets Max

Depth of embedding: Although embedded clauses may not necessarily involve syntactic movement, they generally involve an accumulation of syntactic operations whose number and nature vary according to the type of embedded clauses (relative, adverbial, or complement clauses): presence of a complementizer (e.g., *que* 'that'), additional verbal inflection, or morphological tense/mood dependencies between main and embedded clauses (Delage, 2008; Hamann & Tuller, 2014; Hamann, Tuller, Monjauze, Delage, & Henry, 2007; Tuller, Delage, & Monjauze, 2006). Moreover, since each operation has a processing cost, when operations add up, complexity increases. The embedding of subordinate clauses within other embedded clauses thus increases the cost of the syntactic processing due to its deep embedding. The following examples describe the increasing complexity of utterances due to an increase of syntactic operations, including multiple embedded clauses.

(7) Un cadeau ! [Non-verbal utterance]
'A gift!'
(8) Jean veut un cadeau. [Verbal utterance]
'John wants a gift'
(9) Je pense [que Jean veut un cadeau] [Single embedding]
'I think that John wants a gift'
(10) Vous imaginez [que je pense [que Jean veut un cadeau]] [Multiple embedding]
'You imagine that I think that John wants a gift'

Both of these syntactic aspects (movement and embedding) have been demonstrated to be relevant at a developmental level. Indeed, young TD children, as well as children with DLD, produce object questions with a *wh*-word in-situ more frequently than object questions containing movement of the object (Jakubowicz, 2011). As for embedding, its complexity influences children's syntactic acquisition since complex utterances are indeed mastered later in typical development. Thus, after the age of six to seven, rather than producing new structures (for the most part mastered), children are facing a progressive increase in the complexity of produced utterances, with a deeper degree of embedding (Delage, 2008; Delage & Tuller, 2010; Hamann & Tuller, 2014). Therefore, Hass and Wepman (1974), among others, underlined a significant age effect on the number of embedded clauses measured with spontaneous language samples produced by 167 English-speaking children aged three to thirteen (see also Hamann *et al.*, 2007; Leadholm & Miller, 1992; Loban, 1976; Reilly, Losh, Bellugi, & Wulfeck, 2004; or Soares, 2006, who highlighted the same progression in the complexity of produced utterances with age).

Aim and prediction of the present study

Like Jakubowicz (2005, 2011), we hypothesize a direct link between children's increased use of complex syntax and the maturation of their working memory capacities, with the former being predicted by WM. The syntactic complexity of certain sentences (e.g., with embedded clauses) is assumed to place a heavy load on the child's working memory capacities which are limited and still developing. Working memory capacity is expected to increase through normal maturation, thus making essential resources more available for the processing of complex structures. In atypical language acquisition, such as in DLD, limitations in working memory persist with age and should consequently impede the mastery of complex grammatical sentences (Delage & Durrleman, 2018; Durrleman & Delage, 2016; Jakubowicz, 2011; Jakubowicz & Tuller, 2007). We could imagine that, like a 'bottleneck', working memory capacities impose limits on the processing of complex sentences. This bottleneck would limit the ability of young children and children with DLD to comprehend and produce complex sentences. When this working memory capacity increases with age, the necessary resources to process complex syntax become available.[8]

The current study aims to determine whether there is a predictive relationship between WM capacities and the processing of complex syntax in DLD as well as in typical development across a wide range of ages (six to fourteen). With various tasks that assess both working memory and complex syntax, we first attempt to replicate two results previously observed: (1) syntactic abilities and WM performance increase with age in both groups; and (2) syntactic abilities and WM performance improve more slowly in children with DLD, revealing severe and persistent deficits both in syntax and WM. These two results are actually well supported by the literature (see Jakubowicz & Tuller, 2007; Montgomery, Magimairaj, & Finney, 2010, Montgomery *et al.*, 2016; as well as Henry & Botting, 2017, for reviews on these topics), but need to be confirmed in our sample. In the light of the results of previous studies (e.g., Montgomery & Evans, 2009; Montgomery *et al.*, 2008), we also expect that complex spans predict syntactic performance better than simple spans in both groups.

Until now, such a link between complex syntactic abilities and working memory in DLD has received relatively little attention (Durrleman & Delage, 2016; Frizelle & Fletcher, 2015; Marinis & Saddy, 2013; Montgomery & Evans, 2009; Montgomery *et al.*, 2018). However, the implications of the presence of such a relationship seem

[8]Note, however, that in a connectionist approach (see MacDonald & Christiansen, 2002), language experience, and particularly fluency with syntax, can also change with age, which contributes to another way to reduce this bottleneck.

to be of the utmost importance in the understanding, as well as in the remediation, of difficulties encountered by children with DLD.

In this study, we intend to extend the previous studies on this topic by (1) broadening the type of WM tasks used (simple versus complex) and reducing the role of language in these tasks; (2) broadening the type of linguistic tasks used for syntactic assessment (e.g., production, comprehension, and repetition); (3) broadening the types of syntactic structures examined (varying in embedding and movement); and (4) testing the strength of the predictive relationship between syntactic processing and WM (rather than using a correlational approach).

1. We vary verbal working memory measures, using several tasks for both simple and complex spans. Some of these tasks do not depend upon language representations; for example, serial order reconstruction and counting span tasks. These tasks allow us to focus on WM components while neutralizing any potential influence of language. This is not the case for language-based tasks like digit span and listening span used by Montgomery and Evans (2009) and Durrleman and Delage (2016).
2. We evaluate not only the comprehension of complex utterances (as in Montgomery & Evans, 2009, Montgomery *et al.*, 2018, or Marinis & Saddy, 2013, for passives), the repetition of such utterances (as in Frizelle & Fletcher, 2015), or the elicited production of a particular structure (as in Durrleman & Delage, 2016, for clitics), but we assess the complex grammar in all these modalities (comprehension/repetition/production). To do this, we use, for example, elicitation tasks and analysis of spontaneous production samples which yield different yet complementary information about children's production of complement clauses (Steel, Rose, Eadie, & Thornton, 2013).
3. Research on syntactic complexity has often been limited to only one aspect (such as syntactic movement, as in Durrleman & Delage, 2016) or one structure (relatives, passives, or pronouns in studies such as Frizelle & Fletcher, 2015, or Marinis & Saddy, 2013). Based on a more precise definition of syntactic complexity, we include a large variety of sentences for which two factors of syntactic complexity are manipulated: the number of syntactic movement operations and the depth of embedding.
4. Most of the studies cited above have examined the links between working memory and syntax by using simple correlations, an approach which cannot provide information about the direction or causality of this relationship. That is why, in this study, we are searching for predictive links by means of regression analyses. Moreover, the only study (Frizelle & Fletcher, 2015) that used regression analyses was restricted to one specific structure (relative clauses) in one particular modality (repetition).

Method

Participants

Twenty-eight children with DLD, aged 5;0 to 14;6 (M = 8;10, SD = 2;0, 22 boys, 6 girls[9]) were selected for the experiment. The majority of these participants were diagnosed by

[9]This corroborates the classical prevalence stated in the literature with three boys affected for one girl (Hulme & Snowling, 2013).

speech and language therapists working in private clinics in France or Switzerland via standardized tests classically used in clinical practice. For seven children, the diagnosis was performed in France by multi-disciplinary teams in specific centres (centres for language disorders and learning disabilities). All diagnoses of these children included syntactic deficits (with scores less than 2 standard deviations, the criterion used in Switzerland and France to diagnose DLD, CIM 10; De La Santé, 1993), as evaluated by standardized batteries commonly used by language therapists, such as EXALANG 5–8 (Thibault, Helloin, & Croteau, 2010), which include both expressive and receptive assessments. Hearing status as well as articulation were checked by specialized clinicians. At the time of the study, all participants were receiving speech-and-language therapy. Performance of these children was compared with that of 48 typically developing control children aged 5;2 to 12;9 ($M = 9;0$, $SD = 2;4$, 23 boys, 25 girls), recruited from local schools, who did not present any academic or language difficulty according to their teachers and parents, and who had never received speech or language therapy. Descriptive data on participants are given in Tables 1 and 2, including age and gender of children and parents' education level,[10] as well as, for participants with DLD, characterization of language area affected and comorbid difficulties according to their Speech and Language Therapists (SLT).

All participants were strictly monolingual French-speaking, lived in the same border region (including Geneva and its Swiss and French outskirts) and performed within the normal percentile range (⩾ 10th, which corresponds to an IQ of 80) in non-verbal reasoning, assessed via Raven's Colored Progressive Matrices (Raven, Court, & Raven, 1998). Children with DLD obtained a mean score of 27.2 (SD = 5.5) and control children of 28.6 (SD = 6.2) for this non-verbal task. We ensured that the groups did not differ in chronological age ($t(74) = 0.3$, $p = .3$) or in non-verbal reasoning ($t(74) = 1.0$, $p = .6$). Approval for this study was obtained from the Ethics Committee of the Faculty of Psychology, at the University of Geneva. Parents of the participants gave informed, written consent for their children to participate in the research.

Material and procedure

All children were tested individually in the speech and language therapist's office (for children with DLD) or in school (for controls). Their answers were (digitally) recorded for subsequent transcription and coding. All testing sessions were transcribed, coded, and checked twice by two different experts.

To assess working memory performance, we used three simple-span tasks (a–c) and three complex-span tasks (d–f) which involve dual-processing. When the child failed two or three times consecutively on the same task, the task was discontinued. Syntax was evaluated in three different contexts (g–i): comprehension, repetition, and spontaneous production of complex sentences. Finally, Raven's Colored Progressive Matrices (Raven *et al.*, 1998) allowed us to assess the non-verbal reasoning ability of participants. Table 3 summarizes these different tasks and the measures we used for each of the tasks.

(a) *Forward digit span* (WISC IV; Wechsler, 2005). This task consists of orally presenting a series of digits increasing in length from 2 to 9 to the participants, who then have to immediately repeat them aloud in the same order

[10]Performance of children did not significantly differ for this aspect (educational level) on WM or syntax measures, whichever group (controls, DLD) or the parent (mother, father) was considered.

Table 1. Descriptive data on control participants

Participants	Age (y;m)	Sex	Mother's level of study	Father's level of study
1	5;2	m	⩾ HSD	⩾ HSD
2	5;3	f	⩾ HSD	⩾ HSD
3	5;6	f	⩾ HSD	⩾ HSD
4	5;8	m	⩾ HSD	⩾ HSD
5	5;9	m	< HSD	< HSD
6	5;11	f	⩾ HSD	⩾ HSD
7	5;11	f	⩾ HSD	⩾ HSD
8	6;0	f	< HSD	< HSD
9	6;1	f	< HSD	⩾ HSD
10	6;2	m	< HSD	< HSD
11	6;2	m	⩾ HSD	⩾ HSD
12	6;4	m	⩾ HSD	⩾ HSD
13	6;5	f	⩾ HSD	⩾ HSD
14	6;6	f	⩾ HSD	⩾ HSD
15	6;8	m	⩾ HSD	⩾ HSD
16	6;8	f	⩾ HSD	⩾ HSD
17	8;2	f	⩾ HSD	⩾ HSD
18	8;3	m	⩾ HSD	< HSD
19	8;5	m	⩾ HSD	< HSD
20	8;8	f	⩾ HSD	< HSD
21	8;8	m	< HSD	⩾ HSD
22	9;0	m	⩾ HSD	⩾ HSD
23	9;1	f	⩾ HSD	⩾ HSD
24	9;2	m	⩾ HSD	< HSD
25	9;3	m	⩾ HSD	< HSD
26	9;3	m	⩾ HSD	⩾ HSD
27	9;4	f	⩾ HSD	⩾ HSD
28	9;4	f	⩾ HSD	< HSD
29	9;4	f	⩾ HSD	⩾ HSD
30	9;6	f	⩾ HSD	⩾ HSD
31	9;11	f	⩾ HSD	⩾ HSD
32	9;11	m	⩾ HSD	⩾ HSD
33	11;0	m	⩾ HSD	< HSD
34	11;1	m	⩾ HSD	⩾ HSD

(*Continued*)

Table 1. (*Continued.*)

Participants	Age (y;m)	Sex	Mother's level of study	Father's level of study
35	11;1	m	⩾ HSD	< HSD
36	11;1	f	⩾ HSD	⩾ HSD
37	11;2	m	< HSD	< HSD
38	11;5	f	⩾ HSD	⩾ HSD
39	11;9	f	< HSD	< HSD
40	11;11	f	⩾ HSD	< HSD
41	12;0	f	< HSD	< HSD
42	12;1	m	⩾ HSD	⩾ HSD
43	12;1	f	⩾ HSD	< HSD
44	12;4	f	⩾ HSD	⩾ HSD
45	12;5	f	⩾ HSD	⩾ HSD
46	12;5	m	⩾ HSD	< HSD
47	12;7	m	⩾ HSD	< HSD
48	12;9	m	⩾ HSD	< HSD

Note. HSD = High-school degree.

(b) *Non-word repetition* (BELEC; Mousty, Leybaert, Alegria, Content, & Moraïs, 1994). This task is composed of 40 non-words increasing in length (1–5 syllables) and in phonological complexity (with Consonant–Vowel and Consonant–Vowel–Consonant structures), such as *moga*, *juséga*, *kragrinblan*, *panilèfévu*, *praublifrouklébro*.

(c) *Word span.* The 'animal race task' (Majerus, 2008; Majerus *et al.*, 2006) is a serial order reconstruction task.[11] Participants listen to a short auditory list of animal names participating in a race; the subjects are then asked to put the animals on the podium in their order of arrival.

(d) *Backward digit span* (WISC IV; Weschler, 2005). In this task, participants are asked to repeat a series of digits in the reversed order.

(e) *Counting span* (Case *et al.*, 1982). In this task, the child is presented with a ring-binder with each page containing a different number of red and blue dots. The child is instructed to count and remember the number of red dots, and then, after *n*-pages (a number which progressively increases), he/she has to recall, in the order of presentation, the number of dots remembered for each page.

[11]Majerus and his colleagues (2006) distinguish between two types of information within the phonological loop: (1) item information, that is, the stored lexical items presented for recall; and (2) serial order information, which refers to the sequential order in which the items are presented. Thus, in the task used in this study, participants do not need to memorize the names of the animals per se, but rather need only to remember the order in which the animals were presented in the list they have previously heard.

Table 2. Descriptive data on participants with DLD

Participants	Age (y;m)	Sex	Mother's level of study	Father's level of study	SLT diagnosis: Language area affected	SLT diagnosis: Comorbid difficulties
1	5;0	m	⩾ HSD	⩾ HSD	Phon. & MS	
2	6;2	m	< HSD	< HSD	Phon. & MS	AD
3	6;3	m	< HSD	< HSD	MS	AD
4	6;8	f	< HSD	< HSD	Phon. & MS	AD
5	6;8	f	< HSD	< HSD	Phon. & MS	AD
6	7;0	f	< HSD	⩾ HSD	Phon. & MS	AD
7	7;1	m	< HSD	< HSD	MS	Stuttering
8	7;7	m	< HSD	< HSD	Phon. & MS	WLD
9	7;7	m	⩾ HSD	⩾ HSD	MS	AD
10	7;9	f	< HSD	< HSD	Phon. & MS	WLD
11	7;8	m	⩾ HSD	⩾ HSD	Phon. & MS	AD & dyspraxia
12	8;1	m	< HSD	< HSD	Phon. & MS	
13	8;1	m	< HSD	< HSD	Phon. & MS	dyspraxia
14	8;5	f	< HSD	< HSD	Phon. & MS	WLD
15	8;11	m	< HSD	< HSD	MS	WLD
16	8;11	m	⩾ HSD	⩾ HSD	Phon. & MS	WLD
17	9;1	m	< HSD	< HSD	MS	AD
18	9;8	m	⩾ HSD	⩾ HSD	MS	WLD
19	9;10	m	< HSD	< HSD	Phon. & MS	WLD
20	9;10	m	< HSD	< HSD	Phon. & MS	WLD
21	9;11	m	⩾ HSD	< HSD	Phon. & MS	
22	9;11	f	< HSD	⩾ HSD	Phon. & MS	
23	10;4	m	< HSD	< HSD	MS	WLD
24	10;8	m	< HSD	< HSD	Phon. & MS	WLD
25	11;0	m	⩾ HSD	⩾ HSD	MS	Anxiety
26	11;4	m	< HSD	< HSD	Lex. & MS	
27	11;6	m	< HSD	< HSD	Phon. & MS	Anxiety
28	14;6	m	< HSD	< HSD	Phon. & MS	WLD

Notes. HSD = High-school degree; phon. = phonology; MS = morphosyntax; Lex. = lexicon; AD = attentional difficulties; WLD = written language disorders.

(f) *Running span* (Pross, Gaonac'h, & Gaux, 2008). This task evaluates the size of the attentional focus and involves updating WM content (without using rehearsal processes, as it is the case for subvocal repetition). The child hears a list of

Table 3. Synthesis: tasks and measures

Domains	Tasks	Measures used
Simple spans (= phonological loop)	***Forward digit span***	No. of correct items
	Non-word repetition	No. of correctly repeated syllables
	Word span *(Serial order reconstruction)*	No. of correct trials
Complex spans (= phonological loop + central executive)	***Backward digit span***	No. of correct items
	Counting span	No. of correct recalls
	Running span	No. of correct recalls
Complex syntax	***Comprehension*** *of complex sentences*	No. of correct responses
	Repetition *of complex sentences*	No. of target structures
	Syntactic analysis of ***spontaneous language*** *samples*	MLU % embedded clauses % multiple embedding

monosyllabic words (e.g., *peau* 'skin', *fil* 'thread', *date* 'date', *peur* 'fear', *ski* 'ski', *noix* 'walnut') without knowing how many words the list contains; he/she is then instructed to recall the last two, three, or four words listed by the experimenter.

(g) *Comprehension of complex sentences* (ECOSSE; Lecocq, 1996, a French adaptation of the well-known TROG; Bishop, 1989). In this standardized task, which was reduced by half and only included complex utterances, the examiner reads a sentence referring to one of four drawings, and the participant's task is to point to the one that corresponds to the meaning of the sentence. The distracter drawings differ from the target sentence by either a lexical or grammatical element. The sentences are divided into blocks composed of gradual syntactic complexity (e.g., *La vache que le chien poursuit est marron; le cercle dans lequel il y a une étoile est rouge* 'the cow that the dog is chasing is brown; the circle in which there is a star is red').

(h) *Repetition of complex sentences* (Delage & Frauenfelder, 2012). The child has to repeat sentences that include embedded clauses whose syntactic complexity varies. Two factors of syntactic complexity are manipulated: the type of relative clause (with one or two movements resulting in different word orders) and the depth of embedding (cf. Table 4).[12] The task consists of 8 control sentences (without embedding) and 16 complex sentences, all containing relative clauses. Control and complex sentences are of the same length (14 syllables per sentence). The repeated sentence is considered correct if the target structure is uttered (e.g., subject relative clause: *qui pleure* 'who is crying') with the expected embedding (here, three levels: *Il pense [qu'elle dit*

[12]As pointed out by an anonymous reviewer, object relatives (OSV) differ from other relatives not only by word order but also by the fact that they have pronominal subjects. If we consider, in the line of Culbertson (2010), that in spoken French subjects clitics are agreement markers rather than an argument equivalent to full DP subjects, we are faced with an additional difference whose influence cannot be explored specifically in this work.

Table 4. Types of complex sentences

Manipulation: type of relative clauses			
+ COMPLEXITY	Subject relative (SVO)	*La maîtresse voit le garçon [qui lit un livre sur Noël].*	*The teacher sees the boy [who is reading a book about Christmas].*
	Object relative (OSV)	*La dame regarde le garçon [qu'elle a invité chez elle].*	*The woman sees the boy [who she has invited home].*
	Object relative with inversion (OVS)	*Le papa cherche la grande fille [que préfèrent tous les garçons].*	*The father picks up the tall girl [that boys prefer].*
Manipulation: depth of embedding			
+ COMPLEXITY	Level 1	*La maîtresse voit le garçon [qui lit un livre sur Noël].*	*The teacher sees the boy [who is reading a book about Christmas].*
	Level 2	*Je crois [que la fille préfère le chien [qu'elle a colorié]].*	*I think [that the girl prefers the dog [that she has coloured]].*
	Level 3	*Il pense [qu'elle dit [que le garçon déteste la fille [qui pleure]]].*	*He thinks [that she is saying [that the boy hates the girl [who is crying]]].*

[que le garçon déteste la fille [qui pleure]]] 'He thinks [that she is saying [that the boy hates the girl [who is crying]]]'). We chose to use a sentence repetition task because it allows us to evaluate precisely the ability of children to produce structures in which complexity is manipulated, which is not the case for spontaneous language analysis or classical elicitation tasks.[13]

(i) *Syntactic analysis of spontaneous language samples*. Spontaneous language samples are elicited during free interview contexts where 60 utterances per child[14] are analyzed. After the initial coding, all transcriptions were checked by an expert linguist who also listened to all of the corresponding audio files.[15] Our measures are (i) 'MLU' (total number of words / total number of sentences); (ii) rate (= proportion) of embedded clauses (number of subordinate clauses / number of verbal utterances); and (iii) rate of multiple embedding (number of subordinate clauses embedded in another subordinate clause / number of verbal utterances). Utterances are parsed using C-units, each unit corresponding to one main clause with all

[13]Hence, in spontaneous language, children have the 'choice' of the structures used. If, for example, they produce no relative clauses in their corpora, this does not necessarily mean that they are unable to produce sentences with this degree of complexity. As for elicited production, it is very difficult to elicit relative clauses with multiple levels of embedding (with levels 2 or 3). Indeed, the existing materials only elicit subject and object relatives with only one level of embedding (see for example Friedman & Novogrodsky, 2004).

[14]These 60 utterances were systematically selected from the fifth minute of the interview in order to obtain a sample where the child was more relaxed.

[15]Transcript reliability was calculated for 10% of the transcripts with percentage agreement above 90%.

Table 5. Pearson correlations between measures of syntax and WM for three groups: all CTRL participants, DLD participants, and age and number-matched CTRL

		Age (CTRL) (N = 48)	Age (DLD) (N = 28)	Age (CTRL) (N = 28)
Complex syntax	Comprehension	**.70*** **	.50 ns	**.57** **
	Repetition	**.63*** **	.25 ns	**.60** **
	MLU	**.54*** **	.06 ns	**.64*** **
	% embedded clauses	**.46** **	.13 ns	**.50** **
	% multiple embedding	**.44** **	.40 ns	.31 ns
Simple spans	Forward digit span	**.61*** **	.33 ns	**.61** **
	Non-word repetition	.41 ns	.32 ns	.45 ns
	Word span	**.71*** **	.20 ns	**.78*** **
Complex spans	Backward digit span	**.69*** **	.16 ns	**.70*** **
	Counting span	**.72*** **	**.53** **	**.74*** **
	Running span	**.62*** **	.44 ns	.45 ns

Notes. ***$p < .001$; **$p < .0023$ (Bonferroni correction).

subordinate clauses attached to it. The following example (11) illustrates a multiple embedding produced by a control child.

(11) CHILD (aged 12): "et puis enfin y a [PR] les animaux qui peuvent parler [SUB1] parce que dans leur réseau au départ on leur a donné [SUB2] une petite machine qui leur permet [SUB3] de parler [SUB4] [NF]"[16]
'And then lastly there are the animals who can talk because in their network they were given a little machine so that they could speak.'

Such embedded clauses may be used more or less frequently by children as a function of individual stylistic choices. To limit this variability and minimalize the diversity of conversation topics, each interview followed the same format, with specific questions about leisure activities.

Main results

Preliminary hypothesis: performance improves with age

As expected, our results revealed a strong age effect for syntax and for WM in control children (CTRL), since age is significantly correlated with almost all measures of syntax and WM in this group of 48 participants (Table 5). Note that, due to multiple variables considered, we performed a Bonferroni correction ($p < .0023$) in dividing the critical p value by the number of comparisons being made.

However, this age effect is largely absent in the DLD population despite the fact that the age range of this population is larger (five to fourteen years) than in the controls (five to twelve years). More precisely, although 5 out of 6 working memory measures

[16]PR = main clause; SUB = subordinate clause; NF = non-finite clause. Numbers indicate the level of embedding of the subordinate clause.

and all language measures correlate significantly with age in control children, only one measure correlates with age in children with DLD (counting span). These results may reflect a dissociation between the normal maturation of syntax and WM in control children and a slower development observed in children with DLD in the same domains. Note, however, that the different number of participants in each group (48 for controls, 28 for DLD) makes it difficult to compare the two groups with respect to these patterns of correlations. Thus, the moderate correlations in the DLD group (for syntactic comprehension or running span for example) are not significant, whereas such levels of correlations are significant in controls due to the higher number of participants. In order to take into account this problem, we have conducted the same analyses with a subgroup of 28 control children, age-matched with DLD children (M = 8;11). Results are presented on Table 5 (in the darker tint) and display the same pattern of correlations except for two correlations that become non-significant (rate of multiple embedding and running span).

Preliminary hypothesis: controls versus DLD

With regard to syntax, Table 6 sheds light on the severe difficulties encountered by children with DLD in this domain since they significantly differ from the control children for all the measures. We conducted other analyses which demonstrate that the difficulties encountered by these children are particularly specific to complex syntax. For instance, in spontaneous language, children with DLD produce significantly less complex sentences (i.e. utterances containing at least one embedded clause) than controls (14% versus 24%; $t(74) = 5.4$, $p < .001$, $d = 1.2$). At the same time, they produce as many simple sentences (without embedded clauses) as controls (60% versus 62%), revealing that children with DLD seem to avoid producing complex sentences when they can make sentences choosing their own words. The fact that children with DLD also produce more non-verbal utterances than controls (25% versus 10%; $t(74) = -5.5$, $p < .001$, $d = 1.2$) further supports this claim.

As expected, the performance of controls and that of children with DLD also differs statistically in all WM measures, with weaker scores in DLD, as shown in Table 7. Figures 1–2 show these results, with the distribution of performance in both groups, for the counting span task and the non-word repetition task.

Moreover, the performance of children with DLD on some simple-span tasks remains below that of younger control children, as illustrated in Figures 3–4, which show differences between young control children aged eight to nine (M age = 8;11, $N = 16$) and the 'oldest' DLD group aged nine to fourteen (M age = 10;5, $N = 14$) for the tasks of non-word repetition and word span (respectively: $t(28) = 5.3.$, $p < .001$, $d = 1.9$; $t(28) = 4.8$, $p < .001$, $d = 1.8$).

Main hypothesis: predictive link between working memory and complex syntax

We proceeded to multiple linear regression analyses in order to test for a predictive relationship between WM and syntax. To simplify these analyses we calculated unit-weighted standardized composite scores for simple and complex spans.[17] Since

[17]We carried out the tests in this manner because all three simple-span tasks were highly correlated ($r = .56$, $p < .001$); similar results were found for the three complex-span tasks ($r = .48$, $p < .001$).

Table 6. Controls versus DLD: complex syntax

		CTRL M (SD)	DLD M (SD)	CTRL > DLD	*Cohen's d*
Complex syntax	**Comprehension** (max. score = 44)	37.9 (4)	28.4 (6.1)	$t(74) = 8.3$ $p < .001$	1.9
	Repetition (max. score = 15)	12.1 (2.9)	3.7 (3.1)	$t(74) = 11.7$ $p < .001$	2.8
	MLU	7.7 (1.1)	5.3 (1.2)	$t(74) = 9.0$ $p < .001$	2.1
	% embedded clauses	24.4% (6.6)	14.2% (9.9)	$t(74) = 4.9$ $p < .001$	1.1
	% multiple embedding	7% (6.1)	2.2% (3.6)	$t(74) = 3.8$ $p < .001$	0.9

Note. p value <.01 (Bonferroni correction).

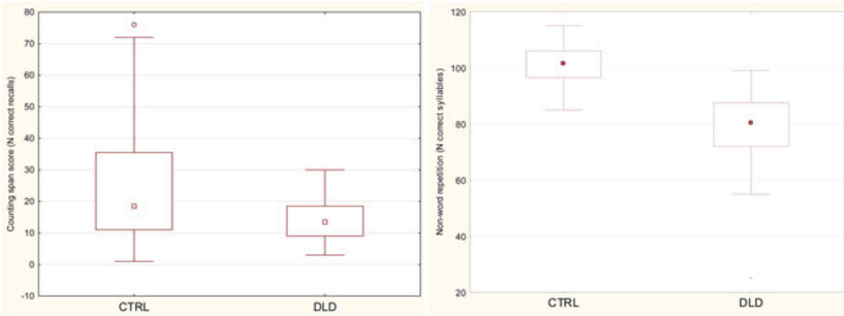
Table 7. Controls versus DLD: working memory

		CTRL M (SD)	DLD M (SD)	CTRL > DLD	*Cohen's d*
Simple spans	**Forward digit span** (max. score = 16)	7.6 (2.2)	5 (1.2)	$t(74) = 5.8$ $p < .001$	1.5
	Non-word repetition (max. score = 120)	101.5 (7)	78.1 (15)	$t(74) = 9.3$ $p < .001$	2.0
	Word span (max. score = 81)	36.8 (13.8)	19.7 (6.8)	$t(74) = 6.1$ $p < .001$	1.6
Complex spans	**Backward digit span** (max. score = 16)	6.5 (2.3)	4.8 (1.7)	$t(74) = 3.4$ $p < .001$	0.8
	Counting span (max. score = 81)	24.9 (17.7)	13.9 (6.2)	$t(74) = 3.2$ $p < .008$	1.6
	Running span (max. score = 12)	5.3 (1.6)	3.2 (2.2)	$t(74) = 4.28$ $p < .001$	1.1

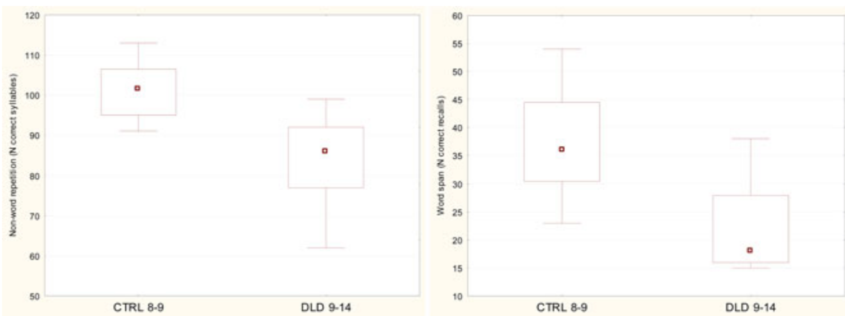
Note. p value < .008 (Bonferroni correction).

correlation matrices (see 'Appendices 1 and 2') point to a possible high degree of collinearity between our four predictors (age, non-verbal reasoning, simple spans, and complex spans), we calculated an index of collinearity of 19.6. This result showed a medium collinearity, as defined by condition numbers of more than 15 (Besley, Kuh, & Welsch, 1980). To deal with this collinearity in our data, we orthogonalized all our predictors to obtain variables which were no longer interdependent (Baayen, 2008). This enabled us to analyze each factor independently.

Moreover, as previously described, simple- and complex-span tasks respectively assess the same theoretical constructs, namely the phonological loop for verbal simple spans, and the additional intervention of the central executive for verbal complex spans. These composite scores were calculated for each group (controls and DLD) separately. We proceeded in the same manner for the orthogonalization of potential predictors.



Figures 1–2. Results for counting span and non-word repetition for controls and DLD children.



Figures 3–4. Results for non-word repetition and word span for a subset of the participants: young control children (aged 8–9) and oldest DLD (aged 9–14).

Indeed, one part of the variance of scores in WM can be attributable to age (the older the children, the better their results). In this case, orthogonalization can remove part of the age-related variance on other predictors and can consequently reduce the interdependency between variables. The possible predictors considered were the composite scores of simple and complex spans, as well as age and non-verbal reasoning. Predicted variables were the different (continuous) measures of complex syntax. The entire set of orthogonalized predictors was entered at a single step. We ran multiple linear regression analyses on each of our five measures of syntactic complexity using the 'lme4' (Bates *et al.*, 2011) and 'languageR' (Baayen, 2010) packages for R.2.11.1 software.

Tables 8 to 12 present the detailed results for these regression analyses conducted in controls and in children with DLD for each measure of complex syntax. For both groups, the combination of simple spans, complex spans, and age explained a significant part of the variance in the comprehension of complex sentences (55% for controls and 50% for DLD). These predictors are also of particular importance in the repetition of complex sentences, with 51% of the variance explained in control children and 58% in children with DLD. In contrast, results in both groups slightly differ when considering spontaneous language measures (Tables 10, 11, and 12). In fact, our findings revealed that complex-span tasks strongly predicted all three measures of spontaneous language in the control group, whereas this predictor does

Table 8. Regression analyses for comprehension of complex sentences

Group : controls				
Significant predictors	B	β	*t value*	*p value*
Simple spans	7.586	1.041	6.791	**< .001**
Complex spans	12.682	1.393	7.318	**< .001**
Age	0.280	1.207	7.215	**< .001**
Non-verbal reasoning	0.030	0.163	1.612	.114
% Explained variance = 55% (F(4,43) = 15.2, p < .001)				
Group : DLD				
Significant predictors	B	β	*t value*	*p value*
Simple spans	6.767	0.769	4.620	**< .001**
Complex spans	8.056	0.799	4.587	**< .001**
Age	0.178	0.601	3.697	**< .01**
Non-verbal reasoning	0.051	0.233	1.600	.123
% explained variance = 50% (F(4,23) = 7.6, p < .001)				

Table 9. Regression analyses for repetition of complex sentences

Group : controls				
Significant predictors	B	β	*t value*	*p value*
Simple spans	6.035	1.132	6.909	**< .001**
Complex spans	7.796	1.169	5.769	**< .001**
Age	0.187	1.106	6.255	**< .001**
Non-verbal reasoning	0.014	0.099	0.947	.349
% explained variance = 51% (F(4,43) = 13.1, p < .001)				
Group : DLD				
Significant predictors	B	β	*t value*	*p value*
Simple spans	4.313	0.965	6.388	**< .001**
Complex spans	3.135	0.613	3.893	**< .001**
Age	0.044	0.295	1.998	.057
Non-verbal reasoning	0.015	0.134	1.017	.319
% explained variance = 58% (F(4,23) = 10.5, p < .001)				

not explain the variance in spontaneous language measures in children with DLD. Interestingly, in this group simple spans are the most important predictor of complex syntax in spontaneous language production.

Table 10. Regression analyses for Mean Length of Utterances (MLU)

Group : controls				
Significant predictors	B	β	*t value*	*p value*
Simple spans	1.082	0.529	2.815	**< .01**
Complex spans	2.799	1.095	4.693	**< .001**
Age	0.060	0.922	4.496	**< .001**
Non-verbal reasoning	0.000	0.015	0.122	.903
% explained variance = 32% ($F(4,43) = 6.5$, $p < .001$)				
Group : DLD				
Significant predictors	B	β	*t value*	*p value*
Simple spans	1.155	0.691	3.517	**< .01**
Complex spans	0.575	0.300	1.461	.157
Age	0.004	0.068	0.357	.724
Non-verbal reasoning	0.018	0.427	2.485	**< .05**
% explained variance = 30% ($F(4,23) = 3.9$, $p < .05$)				

Table 11. Regression analyses for rate of embedded clauses

Group : controls				
Significant predictors	B	β	*t value*	*p value*
Simple spans	9.918	0.432	2.015	.050
Complex spans	21.058	0.734	2.758	**< .01**
Age	0.535	0.732	3.128	**< .01**
Non-verbal reasoning	0.040	0.067	0.473	.639
% explained variance = 11% ($F(4,43) = 2.5$, $p < .05$)				
Group : DLD				
Significant predictors	B	β	*t value*	*p value*
Simple spans	12.216	0.563	2.564	**< .05**
Complex spans	4.669	0.188	0.814	.424
Age	0.116	0.158	0.734	.470
Non-verbal reasoning	0.140	0.258	1.338	.194
% explained variance = 11% ($F(4,23) = 2.0$, $p < .05$)				

In the light of these results, we examined which WM tasks were the most predictive for syntactic measures in spontaneous language production. In order to do this, we repeated the same analyses, this time, however, with seven (orthogonalized)

Table 12. Regression analyses for rate of multiple embedding

Group : controls				
Significant predictors	B	β	*t value*	*p value*
Simple spans	3.882	0.420	2.011	.052
Complex spans	11.757	0.844	3.233	**< .01**
Age	0.266	0.750	3.267	**< .01**
Non-verbal reasoning	0.027	0.095	0.684	.497
% explained variance = 15% ($F(4,43) = 3.1$, $p < .05$)				
Group : DLD				
Significant predictors	B	β	*t value*	*p value*
Simple spans	2.330	0.446	2.075	**< .05**
Complex spans	2.071	0.346	1.538	.138
Age	0.793	0.449	2.142	**< .05**
Non-verbal reasoning	0.040	0.309	1.643	.114
% explained variance = 16% ($F(4,23) = 2.3$, $p < .05$)				

possible predictors: the six WM scores and age. Again, the results revealed different tendencies depending on the group. In control children, the counting span (= complex-span task) is the only WM task which, associated with age, significantly predicts the three syntactic measures: 25% of the variance of MLU ($F(7,40) = 3.2$, $p < .01$),[18] 19% of the variance of the rate of embedded clauses ($F(7,40) = 2.6$, $p < .05$),[19] and 11% of the variance of the rate of multiple embedding ($F(7,40) = 1.9$, $p < .05$).[20] In children with DLD, however, the word span (= simple-span task) explains 35% of the variance of MLU ($F(7,20) = 3.1$, $p < .05$)[21] and 22% of the variance of the rate of embedded clauses ($F(7,20) = 3.6$, $p < .05$).[22]

General discussion

First, our results confirm that WM and complex syntax capacities increase considerably with age in control children, whereas this progression seems to be slower in children with DLD. Note, however, that these differences in changes in performance over time have to be interpreted with extreme caution since only a longitudinal study, following the same children from a young age to adolescence, could confirm that, with age, the maturation timeline of WM capacities differs between the two groups. Our results also show persistent limitations in both syntax and WM in DLD, who obtained lower scores than controls, which has already been described in adolescents

[18]Significant predictors: Counting span ($t = 2.3$, $p < .05$) and Age ($t = 3.5$, $p < .01$).
[19]Significant predictors: Counting span ($t = 2.6$, $p < .05$) and Age ($t = 2.9$, $p < .01$).
[20]Significant predictors: Counting span ($t = 2.5$, $p < .05$) and Age ($t = 2.6$, $p < .05$).
[21]Significant predictor: Word span ($t = 3.0$, $p < .01$).
[22]Significant predictor: Word span ($t = 2.1$, $p < .05$).

with DLD (Tuller *et al.*, 2012, for complex syntax, and Weismer, Plante, Jones, & Tomblin, 2005, for WM).

Second, we have demonstrated a close relationship between WM capacities and complex syntax, with simple and complex span explaining a significant part of the variance in the syntactic measures. These findings support Jakubowicz's (2011) hypothesis suggesting that (1) the progressive maturation of WM in typically developing children explains, at least in part, the increase of the mastery of complex syntax with age; and (2) the WM deficits observed in children with DLD limit their ability to process complex syntax. Nevertheless, one could venture an objection: since it is known that WM is strongly related to general IQ level (see for example Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008), it is perhaps general IQ level that predicts syntax development rather than WM itself. However, as already mentioned, our results cannot be explained in this way since predictors entered in regression analyses were orthogonalized in order to neutralize their reciprocal influences (and especially the influence of non-verbal reasoning on WM performance). Moreover, non-verbal reasoning capacities, entered as potential predictors, almost never appeared as a significant predictor for complex syntax performance. Since age alone cannot explain the strong predictive relationship observed between WM and syntax, these results thus argue for a specific relationship between WM and syntax.

Another observation supports this particular relationship between WM and complex syntax (and not grammar in general). In our analysis of the spontaneous language samples, we computed the proportion of complex and simple sentences. Whereas WM measures correlated with the complex syntax measures, neither simple nor complex spans did so with the proportions of simple verbal or non-verbal utterances. As a consequence, it seems that complex syntax depends specifically on the WM capacities of children, as has been demonstrated by previous studies (e.g., Frizelle & Fletcher, 2015). Similarly, further analyses of the results from the repetition of complex sentences task show that complex spans predict children's performance on deep embedded clauses (with at least two degrees of embedding) rather than on simpler embedded clauses (with only one degree of embedding). Furthermore, subject relatives, which are simpler constructions than object relatives (since they do not involve the disruption of the canonical structure), are not predicted by WM results, in contrast to the more complex object relatives.

Table 13 offers a synthesis of our main results in comparing the common and specific patterns for controls and DLD children. The results showing a role of WM in syntactic performance of both populations can be understood straightforwardly for sentence comprehension and repetition since these tasks logically require the storage of the verbal material in order to respectively (1) give the right answer for comprehension or (2) recall the sentence for repetition. As for our measures of spontaneous language, the results may be surprising since it is, a priori, less obvious that producing language in a natural context requires an abundance of computational resources in terms of memory processing, particularly for children with typical language development. Yet, even in a natural context of conversation, people have to plan their utterances by remembering the topic of the conversation, taking into account the feedback of their conversation partner, preparing a response in advance, and articulating their response at the appropriate moment (Corps, Gambi, & Pickering, 2018). It is, therefore, not surprising that such cognitive process tax participants' WMs. In this case, the additional processing required by complex syntax could produce an overload in sentence production, which is consistent with

Table 13. Synthesis of main results: common and specific patterns in the two groups

	Common patterns in both groups	Specific patterns	
		Control children	Children with DLD
Comprehension of complex sentences	Predicted by **simple** and **complex** spans		
Repetition of complex sentences	Predicted by **simple** and **complex** spans		
Mean Length of Utterances		Predicted by **complex** spans	Predicted by **simple** spans
Rate of embedded clauses			
Rate of multiple embedding			

the effects of complex spans observed in control children. The fact that only simple spans predict complex syntax (in spontaneous production) in children with DLD could then be explained by the fact that language production for these children is more difficult than comprehension and repetition tasks where their other (lexical and discursive) difficulties intervene less. In spontaneous production, all their language difficulties influence language processing, which could explain why even simple resource processing, such as the ability to maintain verbal material, impacts their spontaneous language production.

Although controls and DLD results follow the same pattern overall, with simple and complex spans explaining a large part of variance of their scores in the comprehension and repetition of complex sentences, we have identified some differences between the two groups regarding which WM tests best predict syntactic performance in spontaneous language. Indeed, complex spans, and in particular the counting span task, explain a significant part of the variance in these measures in control children, whereas simple spans, and more specifically the serial order reconstruction task, do so in children with DLD. This is of particular interest since language aspects are minimized in these specific WM tasks. In fact, in the counting span task, children need to exclusively manipulate numbers from one to nine (all numbers being monosyllabic in French) and, in the serial memory task, children only have to remember the order of animals participating in the race and not their actual names. Consequently, these tasks rely less on language representations as compared to other WM tasks, such as the listening span task in which the child needs to retain the last word of a previously heard sentence and to give a semantic judgement on the same sentence. The fact that the two tasks that depend least on language best predict performance in complex syntax supports the conclusion that WM specifically predicts complex syntax and that this link cannot be explained by inter-individual differences in language.

Why are certain aspects of complex syntax predicted by different WM tasks in controls and children with DLD? Indeed, the fact that only simple and not complex spans predict syntactic complexity measures in spontaneous language samples of children with DLD raises some questions, since previous results (such as those of Frizelle & Fletcher, 2015) pointed to specific links between complex spans and complex syntax. One explanation for this discrepancy refers to the nature of the serial order reconstruction task, a task that was not used by Frizelle and Fletcher. In this task, only the serial order of words has to be maintained and recalled, a condition that echoes word order in sentence processing, a component that we know is particularly difficult for children with DLD, especially when sentences do not follow the canonical word order of their language (see a.o. Montgomery, Gillam, Evans, & Sergeev, 2017). Another explanation can be given on the basis of our data. Due to their well-known difficulties in sustained attention (see Ebert & Kohnert, 2011, for a meta-analysis), children with DLD lack the necessary processing resources to complete complex span tasks efficiently, in particular the counting span task, which has been shown to be linked to sustained attention (Magimairaj & Montgomery, 2013). In other words, the dual-processing involved in these tasks (which require storage and simultaneous processing) may lead to a floor effect which reduces inter-individual variability and makes it difficult to find a relation with complex syntax.[23] Figure 1, which illustrated descriptive data for the counting span task, seems to support this hypothesis. Indeed, DLD performance is not only lower than that of controls, but is also more homogenous. This graph contrasts with the one describing the non-word repetition task (Figure 2), a simple-span task, for which the performance of the two groups is more similarly distributed.

Several studies support the idea that attentional difficulties in children with DLD, particularly in selective attention processing, influence their WM performance. Majerus *et al.* (2009) demonstrated that attentional processing explained more than 30% of the variance in verbal WM capacities, and that it acts as an essential intermediary between short-term memory and linguistics processing. Our study focused specifically on WM. However, as underlined by a large number of studies (see Henry, Messer, & Nash, 2012), attentional deficits are recognized in DLD, 20–40% of children with language impairments having co-occurring attention-deficit hyperactivity disorder (Cardy, Tannock, Johnson, & Johnson, 2010). In fact, attentional difficulties were observed in 8 participants, 28% of the sample, in the present study (see Table 2). However, we did not collect any data on attention skills, and thus we cannot distinguish between the role of working memory and of attention. Since attention is likely a part of working memory (see Cowan, 2005, or Oberauer, 2013), future research should examine the role of attention in the syntactic performance of children with DLD as well.

Returning to the word span task, which tests short-term memory for serial order, we should mention that previous results showed that atypical populations, including children with dyscalculia and dyslexia, present difficulties in serial order reconstruction tasks (Attout & Majerus, 2015; Martinez-Perez, Majerus, Mahot, & Poncelet, 2012). Our study also reveals that children with DLD encountered difficulties in this task; more specifically, this task predicts a significant part of MLU and rate of embedding variance. Since during a serial order memory task children have to remember/store items they have previously heard, they need to plan the order of linguistic elements in advance when producing complex sentences. It thus

[23]Note that although Frizelle and Fletcher did not evoke such a floor effect for the performance of their children with DLD, the simple analysis of the standard deviations obtained by their participants pointed in this direction. Indeed, scores of children with DLD (aged six to seven) and of age-matched TD (aged four) displayed similar variability for scores in simple-span tasks (in digit, word, and non-word recalls) but less variability on complex-span tasks for participants with DLD, especially for counting span and backward digit span.

seems that similar mechanisms underlie serial order memory tasks and the production of complex sentences since in both cases the linearization of verbal elements is involved. Thus, the fact that in this study children with DLD score lower in serial memory tasks could explain why this population, in particular, avoids producing complex sentences in their spontaneous language.

In sum, the results of this study show a strong predictive relationship between WM and complex syntax.[24] Even though our results should be treated with caution due to the relatively small sample of participants with DLD, they are supported by other studies that used larger cohorts (117 children with DLD in Montgomery *et al.*, 2018). We thus think that our results have clear clinical implications. Indeed, if WM limitations in children with DLD truly predict complex syntax deficits in this population, it would then be appropriate to train the WM of this population. Further studies should therefore investigate the impact of a motivated and specific WM rehabilitation programme on syntactic performance in children with DLD, a particular need which had already been formulated by Montgomery (2002): "Structuring intervention with students with DLD to include training of cognitive processes would seem to be important […] we propose that this process should consider other reliable sources of emerging evidence, particularly from psychology, to support the use of alternative treatment approaches such as memory training with students with DLD" (Montgomery *et al.*, 2010, p. 88). Surprisingly, while intensive WM training programmes inundate the market (with programmes such as *Cogmed*: Klingberg *et al.*, 2005; or *Jungle Memory*: Alloway, Bibile, & Lau, 2013), to the best of our knowledge no scientific study analyzing the effect of such training on the language of children with DLD that respects the methodological principles (such as the use of control groups) has been published. Even if prior studies, which were often conducted with typically developing participants, revealed relatively little transfer of skills (Melby-Lervåg & Hulme, 2013), other studies including children with intellectual disabilities (see Danielsson, Zottarel, Palmqvist, & Lanfranchi, 2015, for a meta-analytic review) or adults with aphasia (Eom & Sung, 2016; Zakariás, Keresztes, Marton, & Wartenburger, 2016) are clearly more promising. Finally, we believe that the results of our study could influence the conceptualization of new WM training programmes. These would differ from existing programmes which include a large proportion of visual WM tasks, such as Cogmed, by including training activities targeting specific verbal WM. More precisely, training activities would focus on the working memory aspects that have been shown to be predictive of syntactic performance, such as serial order WM in DLD. Such tailor-made WM intervention programmes could be more effective but still require further empirical support (Majerus, 2016). Specifically on this topic, we recently conducted such a WM training study which shows improvement of complex syntax in children with DLD, more precisely on accusative pronoun production, a clinical marker of DLD in French (Stanford, Durrleman, & Delage, in press).

Authors' note. The corresponding author and the co-author confirm that they do not have any conflicts of interest to declare.

[24]As pointed out by an anonymous reviewer, we included only children with severe language disorders (due to the criterion used in French-speaking countries). Results may have been different if we had included children with less severe deficits, using Anglo-Saxon criteria.

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Appendices

Appendix 1. Correlation matrix between potential predictors in control children

	Age	Simple spans	Complex spans	Non-verbal reasoning
Age	**1.00**			
Simple spans	0.68	**1.00**		
Complex spans	0.80	0.76	**1.00**	
Non-verbal reasoning	0.84	0.62	0.75	**1.00**

Appendix 2. Correlation matrix between potential predictors in children with DLD

	Age	Simple spans	Complex spans	Non-verbal reasoning
Age	**1.00**			
Simple spans	0.38	**1.00**		
Complex spans	0.48	0.52	**1.00**	
Non-verbal reasoning	0.52	0.52	0.52	**1.00**

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