Verbal Short-Term Memory Underlies Typical Development of “Thought Organization” Measured as Speech Connectedness

Natália B. Mota1,2, Renata Callipo3, Lígia Leite3, Ana R. Torres1, Janaina Weissheimer1,3, Silva A. Bunge4, Mauro Copelli2, and Sidarta Ribeiro1

ABSTRACT— Formal thought organization obtained from free speech, a key feature for psychiatric evaluations, has been poorly investigated during typical development. Computational tools such as speech graph connectedness (LSC) currently allow for an accurate quantification in naturalistic settings. LSC’s typical development is better predicted by years of education than by age. Among beginning readers, the LSC of stories composed of short-term memory predicted reading independently from IQ. Here we set out to test a longitudinal sample (6–8 years old, n = 45, followed for 2 years) to verify whether the LSC is predictive of various memory measures, and whether such relations can explain the correlation with reading. The LSC was specifically correlated with verbal short-term memory performance. The results support the notion that the short-term storage of verbal information is necessary to plan a story. Given the limited sample size, the relationship of this interaction with reading remains inconclusive.

The school is an ideal environment to assess cognitive development and learning, but during the daily routine with dozens of children in the same classroom, it is a major challenge to track the academic and cognitive development of each child. In low- and middle-income countries, children face school challenges related to poverty, such as malnutrition, poor sleeping habits, and chronic stress (Ribeiro et al., 2016; Sigman, Peña, & Goldin, 2014). Moreover, schools in these countries do not have the resources or staffing to adequately track the learning trajectories of individual children. Thus, there is a need for efficient, reliable, and low-cost methods for assessing cognitive development and academic performance on a large scale. Automated computational tools are promising solutions for screening children in naturalistic settings, to identify those who may require early intervention.

The complex interaction between language and memory greatly interests various disciplines that aim at understanding typical and atypical development. Still, interdisciplinary studies remain quite scarce. For instance, while the use of free speech as a window into “thought organization” is at the basis of psychopathology (Cokal et al., 2018; Kaplan & Sadock, 2009; Radanovic, Sousa, Vaiengo, Gattaz, & Forlenza, 2013), there has not been much interest in the typical development of the same process. Formal thought disorder (FTD), a set of psychiatric symptoms including speech poverty, derailment, and incoherence, helps to diagnose pathologies such as schizophrenia (Andreasen & Grove, 1986; Kaplan & Sadock, 2009). If free speech helps to identify the cognitive risks of a schizophrenia patient undergoing FTD, how does it develop in typical individuals?

One of the reasons why psychopathological concepts are hard to translate to the study of typical development...
is because the classical approaches to measure them, still widely in use, rely on subjective methodology. However, computational measures based on psychopathological descriptions of symptoms now allow for a deeper assessment of the question. For instance, FTD symptoms such as aberrant word flow are amenable to precise mathematical estimation. Nonsemantic word graphs, in which each node represents a word, and each directed edge represents the temporal order of consecutive words, have been shown to be quite informative even in the case of the limited samples of oral discourse collected in naturalistic settings, such as clinics or schools (Mota et al., 2012, 2016; Mota, Copelli, & Ribeiro, 2017; Mota, Furtado, Maia, Copelli, & Ribeiro, 2014; Mota, Sigman, Cecchi, Copelli, & Ribeiro, 2018; Palaniyappan et al., 2019).

This “speech graph” approach has been tested and validated for the identification of FTD in schizophrenia in different chronic (Mota et al., 2012, 2014), recent-onset samples (Mota et al., 2017), and across different languages (Mota et al., 2014; Palaniyappan et al., 2019). Using the area under the receiver operating characteristic curve (AUC) as a measure of classification that considers false positives as well as false negatives (0.5 = chance, 1.0 = perfect classification), the speech graph analysis was first applied to a small sample of Brazilian individuals (n = 24), and reached AUC = 0.90 to differentiate individuals with schizophrenia from individuals without it (Mota et al., 2012). The method was automatized and tested on a larger Brazilian sample (n = 60) and it reached AUC = 0.94 to distinguish individuals with and without schizophrenia (Mota et al., 2014). In this study, the speech graph attributes which reflect graph connectedness were the ones that better correlated with negative symptoms associated with cognitive and social impairment (Rho ~ −0.6).

The methodology was then tested on an independent sample, comprised of Brazilian adolescents undergoing a first episode of psychosis, and well-matched healthy controls (n = 42). The graph connectedness of oral reports collected during the first clinical interview was used to predict the schizophrenia diagnosis and symptomatic outcome 6 months later, with an AUC of 0.85 and accuracy of 92%. The study found that connectedness was already highly correlated with negative symptoms (R² = .88) during the first surfacing of schizophrenia symptoms (Mota et al., 2017). Next, the methodology was tested in non-Brazilians undergoing psychosis. In this sample collected in the United Kingdom and comprised of only English native speakers, speech connectedness was correlated with the severity of FTD measured by a specific scale (R = 0.6), with social outcomes correlated with global functioning (R = 0.59), and cognitive deficits correlated with aspects of cognitive performance, such as processing speed and working memory (R = 0.54) (Palaniyappan et al., 2019). Speech connectedness was the only behavioral marker tested that correlated with brain connectivity, as measured by resting state fMRI (R = 0.49) (Palaniyappan et al., 2019).

In all these studies of nonsemantic word graphs, the most useful marker of connectedness was the largest strongly connected component (LSC). When a word is repeated, it closes a cycle in which any two participating nodes are mutually reachable; the LSC corresponds to a special kind of long-range word repetition in which the cycle closed is the largest within the graph assessed. The correlation between LSC and cognitive and negative symptoms represents a direct link to general cognitive and social impairment in patients with schizophrenia (Mota et al., 2014, 2017; Palaniyappan et al., 2019). The higher the symptomatic scores (or the lower the cognitive performance), the lower the LSC—with fewer different words within the largest cycle.

If the LSC declines as cognition decays in psychopathological conditions, does it rise during typical cognitive development? If so, what are the underlying cognitive mechanisms related to it? What attributes of nonsemantic word graphs increase as a child develops? These questions began to be addressed in a sample of typical children who are 6–8 years old (yo), undergoing literacy acquisition, and assessed in the school setting (n = 76) (Mota et al., 2016), which revealed a complex association between speech connectedness and reading skills (Mota et al., 2016). In this study the children were asked to tell stories about images that they had just seen (short-term memory reports), and also stories anchored on autobiographic memories (long-term memory reports). These oral narratives were audio recorded, transcribed, and represented as nonsemantic word graphs. The LSC from short-term memory reports was correlated with the intelligence quotient (IQ) and with “theory of mind” (ToM) measures, and was predictive of the national reading exam performance 5 months later (Mota et al., 2016). The larger the LSC was, the higher the IQ, (ToM), and reading performances (Mota et al., 2016). Interestingly these correlations occurred exclusively in short-term memory reports. As the LSC and reading performance were correlated with both IQ and ToM, a possible explanation would be that IQ and/or ToM mediated an indirect relationship between the LSC and reading. However, after adjustments, it was found that the correlation between the LSC and reading performance was independent from both IQ and ToM (Mota et al., 2016).

Next we investigated the development of LSC in relation to age and education, using a larger sample (n = 214) with a wide range of ages (2–60 yo) and educational levels (0–20 years of education), comprising individuals with and without psychotic symptoms (Mota et al., 2018). Among the typical individuals we found positive correlations with both age and education, but years of education explained the variation better than years of age. While the correlation with education was independent from age, the reverse was
not true. Interestingly, among the psychotic individuals there were no significant correlations with either age or education (Mota et al., 2018).

The present study aims to further explore the potential of speech graph analysis as a tool for the screening of learning difficulties in the school environment. As a first step, it is necessary to more deeply understand the relationship between speech graph attributes and cognitive development. Two prior findings (Mota et al., 2016) established the grounds for the present study. First, it was found that nonverbal IQ and ToM scores could not explain the relationship between the LSC for the story narratives and reading (Mota et al., 2016). This result led us to speculate which other factors could explain this relationship. Secondly, an association was found between speech connectedness and reading only for the short-term memory reports, and not for long-term memory reports based on memories from days to years before the interview (Mota et al., 2016). Building on these initial observations, we hypothesized that speech connectedness might be related to short-term memory or/and working memory—particularly in the verbal domain. We posited that the ability to store and/or simultaneously process a large amount of information for a short period of time would be required to plan well-organized discourse, as indexed by a large LSC in a speech graph. Thus, we predicted that graph connectedness and reading fluency would be correlated, replicating prior results with another measure of reading ability (the time spent to read a list of words and pseudo-words), and that this relation would be mediated by measures of verbal (but not visuo-spatial) short-term and/or working memory.

In the present study, we followed up on a subset of the original sample of second graders from a previous study (Mota et al., 2016) in order to more closely investigate the relationship between speech connectedness and memory measures, and to test whether connectedness predicts cognitive and reading performance in second and third grades. Here we aim to verify whether (1) verbal short-term memory or working memory (but not visuo-spatial memory) performance is correlated with the LSC, (2) the LSC is also correlated with reading fluency and how this correlation progresses through time, and (3) verbal memory performance mediates the correlation between LSC and reading.

**METHODS**

**Participants**
A total of 45 typically developing children (24 male and 21 female, 6–8 yo in 2014, 7.33 ± 0.52, mean ± SD) were recruited from six public schools in Natal, Brazil. These children’s families all had low levels of formal education (parental years of education: 9.09 ± 4.01), and low socioeconomic status (family monthly income: USD 307.85 ± 113.30; average national wage USD 499.77, minimum salary in 2014 USD 195.06) (IBGE, 2014). The study was approved by the UFRN Ethics on Research Committee (permit #742.116), and the data were collected individually for each child during regular class hours within the school setting. Written informed consent was obtained on behalf of each child from their legal guardians at a meeting between experimenters, legal guardians, and teachers. At this meeting the legal guardians were interviewed by a psychiatrist (NBM) that collected information regarding socioeconomic and health conditions of the children. All children who presented any sign or symptom of neurological or psychiatric condition, or underwent any psychological, neurological, or psychiatric treatment at the time of the interview or before, were excluded from the sample. The sample studied here consists of a subsample of the children who participated in our prior study (Mota et al., 2016) comprising only the students who continued in the same schools the following year. The study was approved by the UFRN Ethics on Research Committee (permit #742.116), and the data were collected individually for each child during regular class hours within the school setting.

**Protocol**
Longitudinal data (oral recordings and cognitive performance scores) were collected at four time-points comprising the middle and end of second and third grades of elementary school (6–8 yo, and 7–9 yo; see timeline in Figure 1a). In Brazil, students are introduced to reading in first grade, and they start second grade typically at 7 yo, but in poor regions like the Northeast there is a larger variance in age (IBGE, 2014). For this reason, the children in Brazil are only expected to master reading during third grade, when some of the students still struggle with it. Therefore, we expected that more students would be literate at the end of third grade (2015) compared to the end of second grade (2014). We verified children’s reading fluency using a list of 60 words and pseudo-words and expected to find a better performance in the end of third grade (Figure 1b).

When the students were in second grade (June and July, 2014), we collected verbal reports based on short-term memory. In average, the total time to collect data from one child was 10 min. The verbal reports were collected using the same protocol and the same pictures used in previous studies of speech connectedness (Mota et al., 2014, 2016, 2017, 2018). Using a laptop, we presented three affective photos from the IAPS database (Lang, Greenwald, Bradley, & Hamm, 1993), which has been previously validated in children: one positive (e.g., a baby in a bathtub), one negative (e.g., a plane crash scene), and one neutral (e.g., a truck on a road). Each of these photos was presented for 15 s.
Fig. 1. Methods and concepts: (a) Timeline: Longitudinal protocol applied with time points of each data collection (exact dates and details in methods session). (b) Reading fluency during Grades 2 and 3: Each dot represents each student performance at the end of Grades 2 and 3. Red lines represent individuals that increased reading fluency and blue lines individuals that did not increase reading fluency. (c) Illustration of LSC: Representative example of speech connectedness measured by LSC or the number of nodes at the largest strongly connected component (on which all pairs of nodes are mutually reachable). In the example, a text in Portuguese is represented as a graph (each word represented by a node and the sequence of words represented by direct edges). In red are the nodes comprising the LSC, and in blue are the nodes that are not part of the LSC. (d) High and Low LSC, Reading and Memory performances: Two representative examples of reports represented as graphs, one of high mean connectedness, reading fluency, and memory performance, and another of low mean connectedness, reading fluency, and memory performance.
After the presentation of each image, the children were asked to report on what could be happening in the picture. The participant had to retain the picture in memory, create a story and then report it; that is, they were not allowed to narrate the story while looking at the picture. All reports were limited to a maximum of 30 s (Figure 1c). Two to eight weeks later (August–September, 2014), we administered the Raven’s Progressive Matrices test, a measure of nonverbal IQ (Angelini, Alves, Custódio, Duarte, & Duarte, 1999; Raven, 1936). From the 45 participants, we excluded two individuals who performed below the percentile 25 (one male and one female, both 7 yo), to avoid including children outside a typical development curve.

At the end of second grade (November and December 2014), reading fluency was measured. The reading fluency test consisted of the Words and Pseudowords Task, validated by Salles (2005), in which children are asked to read a list of 60 words and pseudo-words as fast as possible, but slowly enough so that each word would be clearly and correctly pronounced. The participants were informed that some words from the list did not exist in their native language—they were “made up words” (e.g., craftissoca); but, in spite of that, they were told that these pseudo-words could still be read just like “real words.” The score for each child consisted of a ratio of the total number of words read divided by the time in seconds taken to read the whole list of words and pseudowords.

The following year (May and June of 2015), we collected oral reports using the same protocol, and at the end of the same year (November 2015), the same reading fluency protocol was applied. Additionally, during May and June of 2015, the children’s performance on four memory tasks was assessed using the official Portuguese version of Pearson’s Automated Working Memory Assessment (AWMA) package, a PC-based program (Alloway & Alloway, 2012). The scores were calculated automatically by the computer program. This battery includes measures of verbal short-term memory, visuo-spatial short-term memory, verbal working memory and visuo-spatial working memory.

In the verbal short-term memory task (nonwords recall, an adaptive verbal short-term memory task), participants must repeat an increasing list of nonwords in the correct order. This task involves recalling a sequence of nonwords in the order in which they were presented verbally by the computer program. These items were presented at a rate of one per second. For example, the child would hear a group of four nonwords, such as CLIN, BRES, TOI, SIL, and be required to recall these words in the correct order as they initially appeared.

In the verbal working memory task (listening recall test), participants had to listen to sentences organized in blocks of 2, 3, 4, 5, or 6, judge them as true or false and verbally recall the final word of each sentence when prompted by a question mark. The number of sentences increased as a result of the participant’s accurate recalling of the words. For example, consider a block containing the following three sentences:

“Abacaxis jogam futebol.” (Pineapples play soccer).
“Carros têm orelhas.” (Cars have ears).
“Leões têm quatro patas.” (Lions have four legs).

In this case, the child would have to read each sentence aloud, provide a true or false judgment, and then recall the final words in the order they appeared: “futebol,” “orelhas,” “patas” (soccer, ears, legs). For this test, AWMA generates two scores, but only one was considered in this paper: the verbal working memory score, which combines the participant’s ability to process and store information required during the task, and consists of judging the sentences as true or false, and recalling the last words from each sentence.

In the visuo-spatial short-term memory task (Dot Matrix), each participant was shown a $4 \times 4$ matrix in a computer screen, with a red dot marking different locations. At the end of the subject had to recall the location of a dot in a sequence of different locations related to the $4 \times 4$ matrix.

Finally, in the visuo-spatial working memory task (Spatial Recall), the participants were presented with sets of two arbitrary but identical shapes on the computer screen. One of the shapes could be rotated in three possible positions, and had a red dot on top of it in three possible locations. First, the child was asked to indicate whether the shape with the red dot was the same as (or the opposite of) another shape without the dot for each set of shapes. Then, the child was asked to point to the locations where the dot on the rotating shape had been pointing for each display, in sequence.

**Speech Graph Analysis**

The oral reports were transcribed and represented as speech graphs. Whenever a participant spontaneously interrupted the report before reaching 30 s of duration, the interviewer prompted the participant to continue talking. All the new words generated after the interruption were transcribed on a different line. To formally represent a text file as a graph, it was defined as the network $G = (N,E)$ where $N = \{w_1, w_2, w_3, \ldots, w_n\}$ is the set of nodes comprising all different words, and $E = \{(w_i,w_j)\}$ is the set of directed edges linking all the consecutive words in the same line (Figure 1c). Each different line of the transcribed report was represented as a different component (subgraph). A shared word merges different components in a same connected component. Given the graph, we calculated the LSC, defined as the number of nodes at the largest component in which any two nodes were mutually reachable (i.e., node “a” has a directed path to node “b,” and node “b” has a directed path to node “a”) (Figure 1c).
As it is expected that children with better memory performance also talk using more words, this difference in word count could greatly impact the LSC, not because of a more connected discourse, but only because the child used more words in general. In order to control for this verbosity effect, a moving window analysis of graph attributes was performed using windows with length of 30 words, and a step of 1 word from one window to the next. For each 30-word window a graph was plotted and the LSC was calculated. We used all the 30-word graphs contained in each speech sample, up to the last graph with 30 words. The average LSC of all graphs of 30 words for each text file was calculated and used for statistical analysis.

Statistical analysis

First we calculated mean, standard deviation, range (minimum and maximum values), sample size, and tested whether there was a normal distribution for the LSC, memory performance, reading fluency during second and third grades, age, and nonverbal IQ percentile (using Kolmogorov–Smirnov test—KS test) (Table 1). Since the data were not normally distributed, we used nonparametric tests and correlations to test our hypotheses (Spearman’s correlation two-tailed test).

Next, we tested whether reading performance increased from second to third grades, and tested specific cross-sectional and longitudinal relations among speech connectedness, memory, and reading. We aimed to investigate three main hypotheses: (1) verbal short-term memory or working memory (but not visuo–spatial memory) performance is correlated with the LSC, (2) the LSC is correlated with reading fluency and how this correlation progresses through time, and (3) verbal memory performance mediates the correlation between LSC and reading.

To test the first hypothesis, we performed Spearman correlations between the LSC and each of the memory measures (verbal and visuo–spatial short-term and working memory, a total of four correlations). To test the second hypothesis, we correlated the LSC in the middle of second grade with reading fluency at the end of second grade, and the LSC in the middle of third grade with reading fluency at the end of third grade (a total of two correlations between LSC × Reading fluency at different time points). Correction for multiple comparisons was implemented using the Bonferroni correction, considering six comparisons (α = .0083). Finally, to investigate the third hypothesis (which required a corroboration of the previous two hypotheses), we planned to perform a Spearman partial correlation between the LSC and reading fluency, adjusted by memory performance. To account for the large variance on age (6–8 yo), we controlled the positive results found by this factor. All statistical analyses were performed using Matlab software (MathWorks, Natick, MA).

RESULTS

As expected, overall the children performed better on the reading fluency test (list of words and pseudowords) in third grade, in comparison to second grade (Reading fluency second vs. third grade, Wilcoxon Ranksum $p = .0477$, Figure 1b). Thus, the sample became more literate between the two time points (2014 and 2015). As predicted by the first hypothesis, at third grade there was a significant correlation between the LSC and short-term verbal memory performance (Rho $= .41$, $p = .0068$, Figure 2a), but not for the three other memory tasks (verbal working memory, visuo–spatial short-term, or working memory tasks) (Figure 2b–d). Contrary to our hypothesis, at second grade there was only a trend but not a significant correlation between LSC and reading fluency (Rho $= .51$, $p = .0124$; significance did not survive Bonferroni correction) (Figure 3a), and at third grade there was no correlation whatsoever (Rho $= -.03$, $p = .8954$). At both time points there was a substantial amount of missing data for the reading test; the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Descriptive Table of Speech Connectedness (LSC), Memory Performance, Reading Fluency, Nonverbal IQ, and Age</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Descriptive table</strong></td>
<td><strong>Mean</strong></td>
</tr>
<tr>
<td>LSC Grade 2 Mid (30-word graphs)</td>
<td>9.13</td>
</tr>
<tr>
<td>LSC Grade 3 Mid (30-word graphs)</td>
<td>7.39</td>
</tr>
<tr>
<td>Nonwords Grade 3 Mid</td>
<td>89.88</td>
</tr>
<tr>
<td>Listening recall Grade 3 Mid</td>
<td>81.42</td>
</tr>
<tr>
<td>Dot matrix Grade 3 Mid</td>
<td>91.40</td>
</tr>
<tr>
<td>Spatial recall Grade 3 Mid</td>
<td>93.67</td>
</tr>
<tr>
<td>Reading fluency Grade 2 End (words/s)</td>
<td>0.35</td>
</tr>
<tr>
<td>Reading fluency Grade 3 End (words/s)</td>
<td>0.45</td>
</tr>
<tr>
<td>Nonverbal IQ (Raven Matrix–percentile)</td>
<td>74.74</td>
</tr>
<tr>
<td>Age (years)</td>
<td>7.349</td>
</tr>
</tbody>
</table>

Note. Mean = standard deviation (SD); range given from minimum (Min) and maximum (Max) values, $p$ values from normality test (Kolmogorov–Smirnov test—KS test) and sample size.
Fig. 2. Spearman correlations between speech connectedness (LSC) and memory performance at the same time point (Grade 3). (a) Speech connectedness at Grade 3 and verbal short-term memory performance (nonwords test). (b) Speech connectedness at Grade 3 and verbal working memory performance (listening recall test). (c) Speech connectedness at Grade 3 and visuo-spatial short-term memory performance (dot matrix test). (d) Speech connectedness at Grade 3 and visuo-spatial working memory performance (spatial recall test). Plots with black dots represent significant correlations and with gray dots represent nonsignificant correlations. Rho and $p$ values at title of each scatter plot.

Fig. 3. Spearman correlations between speech connectedness (LSC) and reading fluency at longitudinal perspective (Grades 2 and 3). (a) Speech connectedness at the middle of Grade 2 and reading fluency at the end of Grade 2. (b) Speech connectedness at the middle of Grade 3 and reading fluency at the end Grade 3. Rho and $p$ values at title of each scatter plot.
sample size dropped from $N = 43$ to 24 in second grade, and $N = 25$ in third grade (Table 1). For this reason, we could not properly test the third hypothesis—that is, whether verbal memory performance mediates the relationship between LSC and reading. Since the sample presented large age variation, we reassessed the only significant result detected, and adjusted by age. After adjustment, the $R^2$ dropped from .41 to .38, and the $p$ value did not survive the Bonferroni correction ($p$ value increased from .0068 to .0128).

**DISCUSSION**

As predicted, there was a significant association between speech connectedness and short-term memory performance in the verbal domain, but not in the visuo-spatial domain. Verbal short-term memory seems to be required for the oral production of narratives composed from short-term memory, and comprising a large number of different words connected within the same graph component. Verbal short-term memory thus allows for the elocution of a well-connected oral report, in which an initial word or set of words is repeated at the conclusion of the narrative, or from time to time, linking end to beginning. The higher the ability to temporarily store verbal information, the more this information may appear in a story primed by a new picture as a well-connected chain of words. Importantly, the relationship between speech connectedness and verbal short-term memory was in part explained by age.

The correlation between speech connectedness and verbal short-term memory is in accordance with the association between verbal short-term memory and syntactic or grammatical complexity measured from spontaneous speech (Adams & Gathercole, 1996, 2000; Blake, Austin, Cannon, Lisus, & Vaughan, 1994), although the specific associations between speech connectedness measured as LSC and linguistic standard measures of grammar or syntactic complexity are yet to be studied. Children able to perform better in a verbal short-term task (nonword repetition) produced longer utterances and used a greater range of syntactic constructions than children that underperformed in the task (Adams & Gathercole, 2000). In another study, children with better performance on the same verbal short-term memory task produced more detailed stories, with longer utterances (Adams & Gathercole, 1996). Also, in preschoolers verbal short-term memory measured as the ability to remember a sequence of animal names was associated with longer utterances in a sentence imitation task (Blake et al., 1994). All these results are in accordance with Speidel's theory about the processes of learning how to speak (Speidel & Nelson, 1989), which propose that children develop a repertoire of linguistic patterns from the ability to imitate adults' morpho-syntactic constructions, and that this ability is governed by interdependent articulation and phonological memory processes. These linguistic patterns support spontaneous speech, and speech production becomes less demanding (Adams & Gathercole, 2000; Speidel & Nelson, 1989).

The ability to produce well-connected speech, which manifests these linguistic patterns learned through development, can also be interpreted as an expression of a “well-organized” mind in the psychiatric sense, getting away from the lack of pattern that is observed in FTD. In schizophrenia, FTD is related to a reduced linguistic complexity in spontaneous speech, specifically measured by less use of embedded clauses and grammatical dependents (Cokal et al., 2018). The lack of a speech pattern can be measured as a similarity between the spontaneous word trajectory with random word trajectories made with the same words: the sequence of words would not matter. This is exactly what was found in schizophrenia, since the first symptomatic manifestations (Mota et al., 2017). Moreover, in typical development, the more years of education, the farther from randomness is the connectedness of memory reports, an association not found in the occurrence of psychosis (Mota et al., 2018). This suggests that verbal memory is linked to this ability to produce a well-connected report, a measure linked to FTD, and that probably verbal short-term memory is associated with FTD. However, direct studies on clinical samples are necessary to properly investigate this issue. Although we did not investigate clinical samples here, this result also relates to the evidence of verbal memory impairments in schizophrenia (Kanchanatawan, Tangwongchai, Supasitisriwati, Sriswasdi, & Maes, 2018). Mnemonic deficits in schizophrenia patients are replicated with a large effect size independently of task difficulty (Grimes, Zanjani, & Zakzanis, 2017) mostly for episodic memory, and are specifically worse than in elderly subjects with dementia (Kanchanatawan et al., 2018) which may explain the difficulty that schizophrenia patients face to produce well-connected reports (Mota et al., 2014, 2017; Palaniyappan et al., 2019).

Interestingly, speech connectedness was related to performance on a simple span task that required only maintenance of individual items (nonwords) in short-term memory, but not on a complex span task that placed demands on working memory. This result is perhaps surprising, given that complex span tasks have been—relative to simple span tasks—more closely associated with reading comprehension, as well as fluid intelligence (Daneman & Carpenter, 1980). However, in the study on the organization of spontaneous speech in fairly young children, the link between speech connectedness and simple span may be due to the large number of different words that children must store online while planning and producing their verbal short-term
memory report. This finding contributes to the basic knowledge of the relationship between memory and naturalistic narratives, and applications to education and mental health may stem from it.

The ability to plan and report a complex and well-connected story seems to evolve with education and literacy in the absence of any clinical condition (Mota et al., 2018). This likely explains the positive correlation between the LSC and reading performance found with a standard test (Mota et al., 2016). Here we could not replicate the correlations between connectedness and reading fluency during literacy acquisition using a more strictly controlled evaluation (Reading fluency × Regular reading tests). One important limitation that can impact this result is the small sample size (almost half of the sample did not perform the reading tests in second and third grades). Besides that, we found that the association between reading fluency and LSC, although they did not survive the Bonferroni correction, showed a tendency in second grade and faded in third grade as children learn to read (from Rho of .51 to .03). This negative result raises the importance of developmental perspectives to study the triple association between reading, speech connectedness, and memory. Another possible interpretation for this negative result is that different aspects of reading skills can be differentially associated with speech connectedness. Future studies with larger samples and better control of age variance are necessary to disentangle this issue. The lack of verbal IQ measure here is also a limitation to be considered in future studies.

Memory performance during reading acquisition probably explains better the relationship between speech connectedness and reading fluency. For this reason, one needs to consider three important limitations of our study, namely the lack of measures of memory performance during literacy acquisition (here second Grade), as well as the small sample size and the large variance of age, so we cannot be conclusive about the triple association between memory, reading, and speech connectedness. However, the present findings highlight the utility of speech graph analysis as a low-cost, feasible, and naturalistic approach that could be useful to assess elementary school children, with direct implications for cognitive evaluation in naturalistic settings. Moreover, the results contribute to a closer understanding of the relationship between language acquisition and verbal memory, a relationship of great interest for typical and atypical development, allowing a transdisciplinary investigation with possible application for multiple purposes. Understanding how a simple, fast, and noninvasive evaluation such as measuring speech connectedness is associated with cognitive and scholastic performance may help to develop better strategies to assess cognitive development or decline in naturalistic settings.

Acknowledgments—Work supported by UFRN, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), grants Universal 480053/2013-8 and 408145/2016-1 and Research Productivity 308775/2015-5 and 310712/2014-9; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Projects OBEDUC-ACERTA 0898/2013 and STIC AmSud 062/2015; Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco (FACEPE); Center for Neuromathematics of the São Paulo Research Foundation FAPESP (grant 2013/07699-0), Boehringer-Ingelheim International GmbH (grant 270561). We thank the Public Schools that allowed the access to the children and to the school environment, and also helped with the interactions with the families; the Latin American School for Education, Cognitive and Neural Sciences for fostering a rich intellectual environment where our ideas could develop; the participants of project ACERTA for help during data collection; Debora Koshiyama for bibliographic support; Pedro PC. Maia, Gabriel M. da Silva, and Jaime Cirne for IT support.

REFERENCES


IBGE. (2014) Pesquisa nacional por amostra de domicílios contínua - Mensal. Brasilia, Brazil: Ministry of Planning, Budget

NeuralSciencesforfosteringarichintellectualenvironment


IBGE. (2014) Pesquisa nacional por amostra de domicílios contínua - Mensal. Brasilia, Brazil: Ministry of Planning, Budget


Mota, N. B., Copelli, M., & Ribeiro, S. (2017). Thought disorder measured as random speech structure classifies negative symptoms and schizophrenia diagnosis 6 months in advance. *NPJ Schizophrenia, 3*, 18. https://doi.org/10.1038/s41537-017-0019-3


