Trends in Neuroscience and Education 21 (2020) 100142

Contents lists available at ScienceDirect

Trends in Neuroscience and Education

journal homepage: www.elsevier.com/locate/tine

Research paper

The History of Writing Reflects the Effects of Education on Discourse Structure: Implications for Literacy, Orality, Psychosis and the Axial Age

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ARTICLE INFO

Keywords:
Graph
Literature
Bronze Age
Axial Age
Indigenous
Language evolution

ABSTRACT

Background: Graph analysis detects psychosis and literacy acquisition. Bronze Age literature has been proposed to contain childish or psychotic features, which would only have matured during the Axial Age (~800-200 BC), a putative boundary for contemporary mentality.
Method: Graph analysis of literary texts spanning ~4,500 years shows remarkable asymptotic changes over time.
Results: While lexical diversity, long-range recurrence and graph length increase away from randomness, short-range recurrence declines towards random levels. Bronze Age texts are structurally similar to oral reports from literate typical children and literate psychotic adults, but distinct from poetry, and from narratives by preliterate preschoolers or Amerindians. Text structure reconstitutes the "arrow-of-time", converging to educated adult levels at the Axial Age onset.
Conclusion: The educational pathways of oral and literate traditions are structurally divergent, with a decreasing range of recurrence in the former, and an increasing range of recurrence in the latter. Education is seemingly the driving force underlying discourse maturation.

1. INTRODUCTION

Since the *edubas* of Sumer, schools scaffold biological maturation towards the development of complex skills such as reading and writing, which are grounded on the progressive expansion of brain area recycling, memory capacity and retrieval [1-4]. Cognitive development and education are both necessary for the maturation of vocabulary, syntax and grammar [5-7]. At the individual level, discourse structure takes many years to reach full development, and requires many years of formal and informal education [7-9], until the full-fledged maturation of children's oral and written narratives [10-14]. At the historical level, the schooling of readers that become writers led to the gradual development of literature. Literacy is thought to have accelerated cultural evolution by creating a powerful new form of memory with huge capacity for sequential combination and yet, less prone to error [15].

But not everybody benefits equally from formal education. Despite schooling, 1-2% of the population shows a deterioration of discourse during adolescence, as psychotic symptoms develop [16, 17]. Such deterioration is particularly well captured by the analysis of non-semantic directed graphs, which represent oral reports as word

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https://doi.org/10.1016/j.tine.2020.100142
Received 30 June 2018; Received in revised form 22 September 2020; Accepted 24 September 2020
Available online 01 October 2020
2211-9493/

trajectories with precise structural attributes. This approach allows for the early differential diagnosis of psychosis, and quantifies the severity of negative symptoms in an objective manner [18-20]. Interestingly, the same graph attributes that decrease in patients with psychosis – those related to the long-range recurrence of words - rise in typical children when they learn to read and write [21]. This occurs in parallel with academic, IQ and theory of mind development, three important characteristics of social skills and cognitive development [21]. Oral reports of children and adults show that graph measures evolve with educational level in a quite organized manner [9]: While the short-range word recurrence decreases over school years, the lexical diversity, long-range recurrence and graph length increase so as to become more distant from random levels. Importantly, in participants with psychosis these graph measures resist education [9].

Psychosis may represent a trace of immature human language not only at the ontogenetic level, but also at the historical one. It has been proposed to resemble a primitive mental mode, an early trait of civilization that persisted historically as recently as the Bronze Age [22]. According to this hypothesis, human mentality only matured into its current mode during the Axial Age (800-200 BC), a period in ancient history marked by a philosophical, religious, artistic, political, legal, economic and educational boom in Afro-Eurasia [23, 24]. Influential and controversial [25], the concept of Axial Age only recently began to receive empirical attention [26, 27]. Here we analyze Pre- and Postaxial literature using the same metrics employed to investigate psychosis [18-20] and childhood [9, 21] in order to elucidate the question.

We first studied 447 representative literary texts spanning ~4,500 years [28], comprising the following nine Afro-Eurasian traditions: Syro-Mesopotamian (N=62), Egyptian (N=49), Hinduist (N=37), Persian (N=19), Judeo-Christian (N=76), Greco-Roman (N=133), Medieval (n=20), Modern (n=20) and Contemporary (N=31). Various controls were assessed using 287 additional texts, and 275 oral reports. Based on previous findings we focused here on the following graph attributes: number of nodes (N), which accounts for lexical diversity, repeated edges (RE) and the largest strongly connected component (LSC), which respectively measure short- and long-range recurrence, as well as average shortest path (ASP), a measure of the graph length (**Fig. 1A**; see Method).

In light of the conjectures of a saturating change of mentality at the dawn of the Axial Age [23, 24], our previous results lead us to predict that as text age decreases, so would increase the lexical diversity (N), the long-range recurrence (LSC) and the graph length (ASP). On the other hand, short-range recurrence (repeated edges - RE) should gradually decrease (**Fig. 1A**). Finally, the dynamics of graph attributes across the historical record is expected to resemble the ontogenetic changes observed in typical participants [9].

2. METHOD

2.1. Literary Data

2.1.1. Bibliography Selection and Edition

Representative prose texts originally written in English or translated to English were extracted from the public domain of internet, or kindly provided by their authors, and converted to .txt extension and edited to remove prefaces, notes, comments, line breaks, page/tablet numbering and publisher information. Paragraphs were preserved. The removal of symbols, numbers and line breaks was automatized by regular expression syntax of the software Notepad++. Matlab routines were implemented to truncate texts at fixed word lengths (50,000 or 1,000 words, depending on the specific analysis). After editing, all texts were individually verified and manually edited to correct possible mistakes. Text identification and source, time intervals, and dating are detailed in [28].

2.1.2. Control for Arbitrary Selection of Postmedieval Texts

The main literary sample was chosen so as to include major canonical texts of each tradition, but the explosive increase in the size of the textual corpora produced after the Middle Ages makes it impossible to ensure a representative sample of canonical texts. For this reason we investigated a control selection of texts to compare with our main literary sample, comprising 10 random sets of 20 modern and contemporary texts selected using the search engine "Random Page" on the digital library Project Gutenberg, with plays, poetry and non-English versions excluded from the selection (https://www.gutenberg.org/ebooks/search/?sort_order=random). For this control, only the initial 1,000 words of each text were analyzed. The composition of the 10 sets is detailed in [28]. Two texts were randomly selected twice, for a total of 198 different texts analyzed in this control.

2.1.3. Transliterated Originals

As a control for translation effects, a curated sample of 56 original texts was also analyzed (**Suppl. Table S1**), comprising 29 transliterated non-English texts and 27 English originals already included in the initial sample (so that each original text had a corresponding English translation in the literacy data set). The transliterated texts were obtained from the same websites and sections from which the English translation was obtained. The texts were selected based on the availability of both the original and the translation. When necessary, originals were collected in phonetic translation (transliteration). Transliterations that contained non-Latin characters required for the accuracy of the phonetic reproduction were subjected to a replacement by corresponding standard characters (Example: "ṡ̌" replaced with "s").

2.1.4. Poetry

A sample of 60 poetry texts was curated to include representative texts from medieval, modern and contemporary literature (N=20 per category), and used as a control to assess whether the graph patterns of interest can be attributed to a poetical structure. Text identification, time intervals, and dating are detailed in [28].

2.1.5. Text Dates

Text dating information was obtained preferentially by exact (known) dating or time of work conclusion (1). In the absence of this information, dates corresponded to the middle of the historical period when the text was written (2), or to the middle of the author's lifespan (3). Details about the dating employed can be found in **Suppl. Note S1**. A grand total of 734 different texts and 10,316,794 words were analyzed Text sources included the Digital Egypt of the University College London (http://www.ucl.ac.uk/museums-static/digitalegypt/), the Electronic Text Corpus of Sumerian Literature of the University of Oxford (http://etcsl.orinst.ox.ac.uk/), Project Gutenberg (www.gutenberg.org), and The Internet Classics Archive of the Massachusetts Institute of Technology (http://classics.mit.edu/). The texts were further subdivided as created in the Early Bronze Age (before 2100 BC), Middle/Late Bronze Age (2100 BC to 1200 BC), Axial Age (800 BC to 200 BC), or Postaxial Age (200 BC to 2014 AC). There were not enough texts dated between 1200-800 BC to allow for analysis during this period of cultural collapse.

2.2. Oral Reports (Ontogenetic Data)

A grand total of 275 oral reports with 76,740 words were analyzed, comprising 234 oral reports from non-Amerindian participants and 41 from Amerindian participants. Reports from contemporary non-Amerindian participants were pooled from different studies [19-21, 29] plus new samples, comprising a comprehensive dataset described in [9]. The current study added 4 illiterate non-Amerindian adult participants that were not considered in [9]. An age threshold of 12 years old was adopted, given the major changes in discourse structure observed around this age [9]. This study used data from two protocols

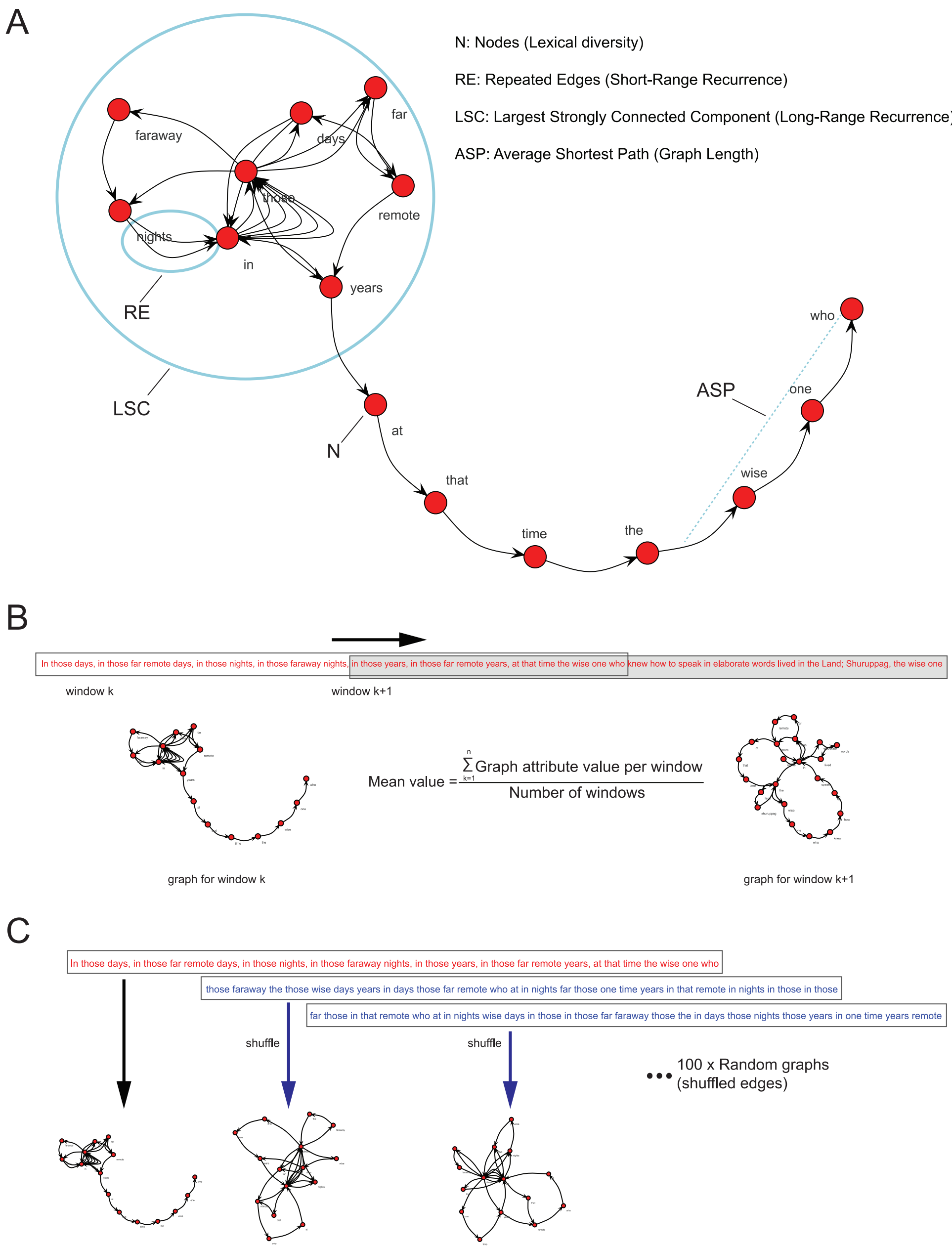

Figure. 1. Nonsemantic word graph analysis of literature texts. The example used here comprises the initial words of "*Instructions of Shuruppag*", one of the earliest texts of the written record [52]. **(A)** The graph attributes investigated comprised lexical diversity (N), long-range recurrence (LSC), short-range recurrence (RE) and graph length (ASP). The ASP corresponds to the mean shortest path considering all the pairs of connected nodes in a graph. Red circles indicate nodes, small black arrows indicate edges. **(B)** Moving windows (length = 30 words, 50% overlap) were used to calculate mean values per graph for the different attributes. **(C)** Graph attributes were calculated for each random graph and averaged to compose the denominator of normalized graph attributes.

approved by the Research Ethics Committee of the Federal University of Rio Grande do Norte (permits #102/06-98244 and #742.116). Signed informed consent was obtained from all participants and also from a legal guardian when necessary, and the study adhered to all relevant ethical regulations. The exclusion criteria were any neurological condition or alcohol/drug abuse.

Non-Amerindian participants with psychotic symptoms comprised 63 participants recruited at three public mental health centers. All the patients that needed to use medication were under medication and this effect on speech graph measures was controlled in other papers that explored these correlations more specifically [9, 19, 20]. These participants were independently diagnosed by the standard Structured Clinical Interview for DSM-IV (SCID) [30] with Schizophrenia disorder (S) (N = 35) or Bipolar disorder type I (B) (N = 28). The use of psychometric scales prior to DSM V reflects the fact that the data were collected as part of earlier studies. Also applied were two standard psychometric scales, the "Positive and Negative Syndrome Scale" (PANSS) [31] and the "Brief Psychiatric Rating Scale" (BPRS) [32], and a socioeconomic-clinical questionnaire (with information regarding age, sex, family income, educational level, marital status, disease duration and onset). There were no participants under 12 years old in the psychiatric group.

Typical participants (with no psychotic symptoms, N = 171, ages 2-90 years old) were recruited from the same health centers (N = 20), from seven urban schools (N = 94, plus an independent sample of N = 18 children in preschool) and from a university (N = 21) in the city of Natal, plus an independent sample of illiterate adults in a semi-rural village nearby Natal (N = 18). In what follows, the concept of different levels of education refers to differences among literate participants (both children and adults) in the amount of formal schooling completed, as self-reported by the participants via a questionnaire. For socio-demographic information of non-Amerindian participants, with a detailed description of medication status and its relationship to the speech graph measure, see [9].

Oral reports produced by all the non-Amerindian participants were based on the same protocol (even for the 2 year old included in the typically-developing sample): The analysis of oral reports focused on answers to three open-ended questions, namely requests for reports of one recent dream, on waking activities in the previous day, and about a negative affective image shown for 15 seconds immediately before the request. The negative image was selected from a widely validated affective images database [33]. All the reports were audio recorded, and produced in Portuguese, which is the native language of both the researcher that was present during data collection (NBM) and of the professionals employed at the commercial provider of transcription service (www.audiotext.com.br). Transcription was blind to the study design, and to the educational and clinical status of the participants. Accuracy of the transcription of oral reports in Portuguese was double-checked by the commercial provider, and then confirmed by one of the researchers (NBM). For each participant, the reports were concatenated, and the final text was represented as a word graph (similar to the graph in **Fig. 1A**). The report protocol was applied in a single session with each participant, individually. Ineffective attempts to obtain oral reports were not observed.

Our initial goal was to sample 20 preliterate Amerindian adults, but we could only obtain up to 18 oral narratives from a single ethnic group (Kalapalo), which were either audio or video recorded by author AG under permit 1712/09 from the National Indian Foundation (FUNAI), and were produced by highly trained oral narrators [34]. To assess whether these measurements could be representative of other Amerindian groups we added a sample of a similar size (N = 23) comprising non-Kalapalo narratives from South America [35-38], Central America [39] and North America [40]. The data came from a public corpus at the University of Campinas (N = 13, [38]; http://www.tycho.iel.unicamp.br/corpus/), from a public corpus at the University of Texas (N = 2 [41]; https://ailla.utexas.org/), and from publications (N = 8; [35-37,39,40]). Overall the Amerindian oral samples were produced in nine distinct languages (Awetí, Bororo, Dena'ina, Ixil, Kadiwéu, Kalapalo, Kamayurá, Kuikuro, and Maxakali) and were transcribed and transliterated by the anthropologists that recorded them, prior to the initiation of our study, as detailed in [28]. The Kalapalo participants were interviewed about their lives, educational experience and knowledge of Portuguese by AG.

The complete set of oral reports was divided in 6 groups according to a "gradient of exposure to literate culture", characterized by degrees of social inclusion in the literate culture.

The first group was considered 'Literate adults' (N = 55, *M* age 26.44 years ± 10.34) and comprised participants more than 12 years of age who had learned to read, presented different levels of education and did not present psychotic symptoms; the second group was considered 'Illiterate adults' (N = 18, *M* age 46.17 years ± 25.21) and comprised participants more than 12 years of age who could not read nor write their own name, and were free of psychotic symptoms; the third group was termed 'Psychosis' (N = 63, *M* age 30.19 years ± 13.10) and comprised individuals with psychotic symptoms, more than 12 years of age, and with different levels of education; the fourth group was termed 'Literate children' (N = 80, *M* age 7 years ± 0.19) and comprised individuals under or equal to 12 years old who were already able to read and write (as verified by having completed at least the first year of elementary education), and were free of psychotic symptoms; the fifth group was termed 'Preschool children' (N = 18, *M* age 3.78 years ± 0.81), and comprised individuals under 5 years of age from urban areas who had not started formal education yet and were free of psychotic symptoms; and the final group was termed 'Amerindian adults' (N = 41, *M* age 65.56 years ± 6.84) and comprised indigenous participants more than 12 years of age. All participants (except for 'Amerindian adults') were interviewed by a psychiatrist (NBM), and screening questions regarding psychotic symptoms were asked of all participants (or legal guardians). One exclusionary criterion for typically-developing participants was to not have any sign or symptom of psychiatric, psychological or neurological suffering at present, or in their clinical history. Information about educational levels was directly obtained from the participant or legal guardian; when a participant indicated never having received any school education, he/she was asked to sign their name; those who failed were considered illiterate.

2.3. Nonsemantic Word Graph Analysis

For the literary raw data, see [28]; for ontogenetic raw data, see [9]. Nonsemantic word graph analysis was performed using the free software *SpeechGraphs* (http://www.neuro.ufrn.br/softwares/speechgraphs). The representation of a text as a graph consisted in assigning to each word a node, and to each sequence of consecutive words a directed edge (**Fig. 1A**). The edges thus represent the temporal sequence of consecutive words. Lemmatization was not performed because we had previously determined - for the purposes of Schizophrenia diagnosis – that nonsemantic word graph analysis yields very similar results for lemmatized [18] or non-lemmatized [19, 20] data. For literary texts as well as oral reports, average graph attributes were calculated using moving windows of 30 words with 50% overlap [19], i.e. steps of 15 words (**Fig. 1B**), and calculating graph attributes for each resulting graph. A total of 4 average graph attributes were calculated for each text file, comprising lexical diversity (the number of nodes = N), short-range recurrence (the number of repeated edges = RE), long-range recurrence (the number of nodes in the largest strongly connected component = LSC) and graph length (the number of edges in the average shortest path = ASP). RE corresponds to the sum of all edges linking the same pair of nodes. LSC corresponds to the number of nodes in the maximal sub-graph in which all pairs of nodes are reachable from one another in the directed sub-graph (i.e. node *a* reaches node *b*, and vice-versa). ASP corresponds to the average length (number of steps along edges) of the shortest path between pairs of nodes of a network. Each pair of nodes that are linked has one or more connecting paths, counted by the number of edges between the nodes. ASP is the average of all shortest paths linking all the connected pairs of nodes in a graph. For an example see **Fig. 1A**. To estimate randomness levels, each 30-word window was shuffled 100 times so as to keep the same words but change their order. This procedure is equivalent to a random permutation of edges [42]. Graph attributes of randomized word windows were then averaged and used to normalize the original average data [20]. To cope with computational cost, texts above 50,000 words were trimmed to this maximum. Figure 5 was obtained with the same data shown in Figure 2B, but using a moving window of width = 200 years and no overlap. The data were analyzed using Excel and Matlab software.

2.4. Exponential model

In order to study the dynamics of graph attributes across different educational levels or across time in literature, the following model was used:

$$f(t) = f_0 + (f_\infty - f_0)(1 - exp(-t/T))$$

where

f_∞ is the maximum asymptotic graph attribute value

f_0 is the initial graph attribute value t is time

T is characteristic time to reach saturation.

The function is the solution to a linear differential equation of first order:

$$df/dt = (1/T)(f_\infty - f) \text{ with initial condition } f(t = 0) = f_0$$

The evolution of each attribute was modeled as an exponential fit to represent accelerated initial development followed by a saturation process of slow progress. This fit to exponentials allows us to identify dynamic properties of each attribute and hence examine in a quantitative manner whether the historical development of literary structure mimics the ontogenetic dynamics of oral discourse [9]. We chose to adjust the data to the simplest possible model, one that only presupposes linear dynamics that converges to a stable fixed point. This provides useful parameters to interpret the data, as indicated by the

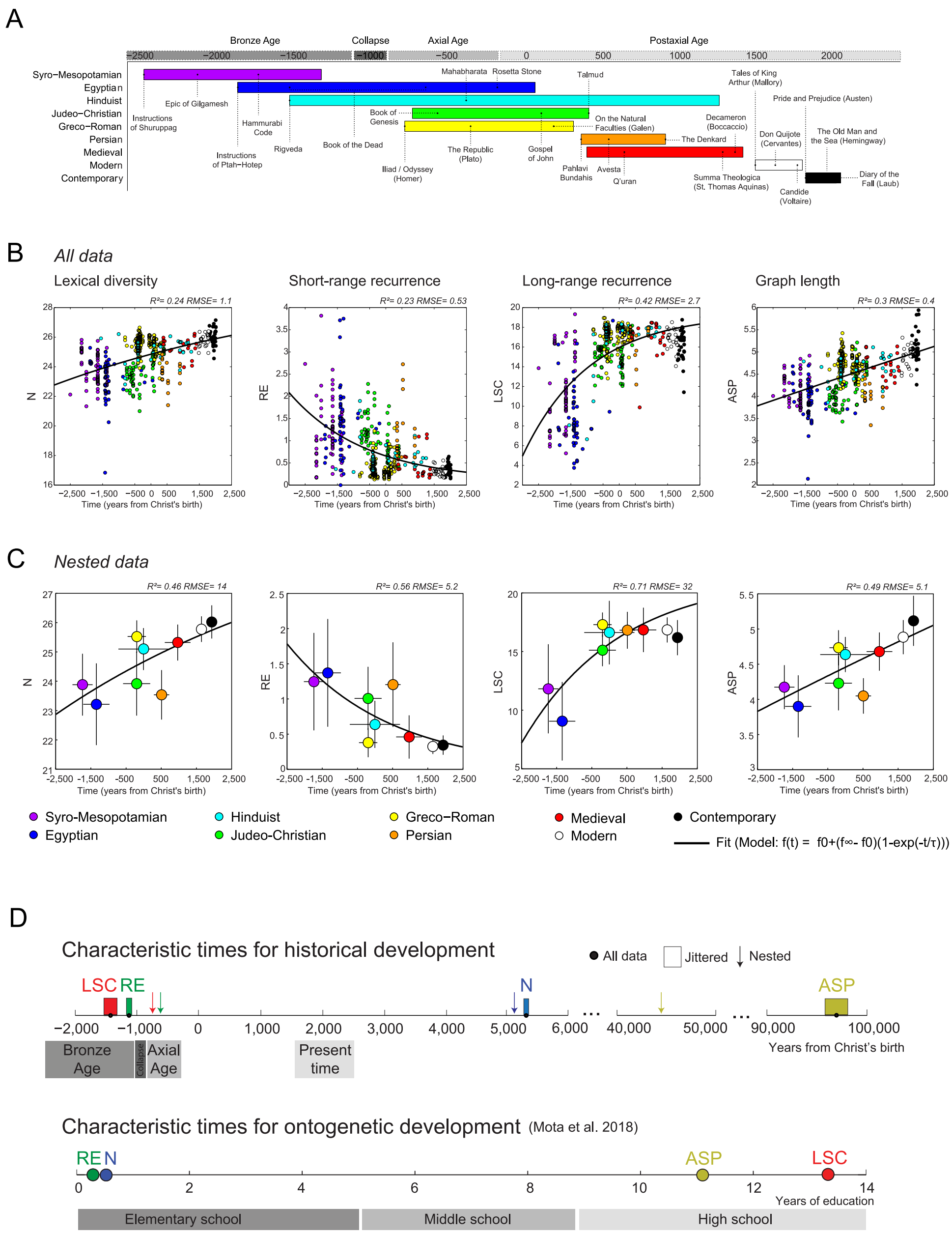

Figure. 2. The historical development of literary structure mimics the ontogenetic dynamics. (A) A corpus of 447 representative texts across 9 Afro-Eurasian literary traditions spanning ~4,500 years and translated to English was investigated by graph analysis as in Fig. 1. **(B)** Lexical diversity increased monotonically over time, while short-range recurrence showed the opposite dynamics. Long-range recurrence and graph length increased over time. The data are well explained by the exponentially saturating model. The data can be further explored at http://www.neuro.ufrn.br/historicaldata. **(C)** The data nested by literary tradition show the same dynamics observed for fits of all individual texts. Each data point represents the mean and standard deviation of the graph attribute for all texts sampled in the tradition. R^2 and root-mean-square error (*RMSE*) indicated on top. For information about the model and parameters used, see Method and **Table 1**. For data on Spearman correlations and goodness of fit using all data points, see **Table 2**. Data on the goodness of fit of the nested analysis is in **Table 2**. Date randomization analysis is in **Suppl. Fig. S1**, date jittering analysis is in **Suppl. Fig. S2. (D)** Top panel: Characteristic times for historical development, indicated by black dots for 'all data', boxes for 'jittered data', and arrow for 'nested data'. The boxes indicate the range of characteristic times for the 1,000 jitter surrogations (details in Method). Bottom panel: Characteristic times for ontogenetic development [9].

agreement with the dating of civilizational collapse between the Bronze Age and Axial periods.

The mathematical analysis of ancient texts is inherently impacted by a plethora of confounds, such as imprecise dating, variable physical support, multiple authorship and versions, editing, censorship, standardization, translation, access to few readers, production by fewer authors, distinct degrees of versification and fictionalization, and stylistic, aesthetic and philosophical differences of both authors and translators [26]. A distinctive limitation is the fact that the transition from orality to literacy can only be timed by approximation, with reference to the earliest texts available (~2,500 BC) [43]. Furthermore, the historical evolution of narrative complexity was surely shaped by different literary schools, since writing at any given time is informed by knowledge and criticism of previous writing forms [44]. The investigation of discourse structure across such different scales of analysis, involving both biological and cultural phenomena, must have categorical limitations that at some point turn potential homology into mere metaphor. Due to their inherently different nature, spontaneous speech and literature, albeit possibly sharing mechanisms for the accumulation of complexity over time, are also expected to differ in many ways.

Notwithstanding these caveats, the historical development of writing should overall resemble typical ontogenetic dynamics, and thus f_∞- f_0 should be positive for N, ASP and LSC but negative for RE. We also expected the characteristic times of the structural development of literature to either precede or coincide with the Axial Age. Research in evolutionary linguistics has described the dynamics of linguistic changes among populations through *s-shaped curve* models, to capture periods of rapid changes followed by periods of stabilization [45].

We first used a non-weighted model considering all data points, and then we repeated the analysis using as input data the average graph attribute from all texts from the same tradition, and weighing the model for the standard deviation of the mean, to control for the different number of texts available from different traditions. To better adjust the fit, we considered lower and upper points to each coefficient, according to the maximum and minimum values expected for each graph attribute and for time (years of historical time), as detailed in **Table 1**. In order to further evaluate the model's goodness of fit, we shuffled the date of

Table. 1
Parameters and rationales for the exponential model.

Coefficient	Rationale for lower point	Rationale for upper point	Start-point
f_∞	0 / no graph attribute can be smaller than 0	30 for N and LSC (graph attributes counted by number of nodes) / maximum number of nodes for 30 word graphs 29 for RE and ASP (graph attributes counted by number of edges) / maximum number of edges for 30 word graphs)	Maximum observed value
	2,500 BC for historical time / earliest written record	Infinite for historical time (Future)	800 BC (Axial Age)
f_0	0 / no graph attribute can be smaller than 0	30 for N and LSC (graph attributes counted by number of nodes) / maximum number of nodes for 30 word graphs 29 for RE and ASP (graph attributes counted by number of edges) / maximum number of edges for 30 word graphs)	Minimum observed value

publication 1,000 times to randomize the order of the vector containing this information, and repeated the Spearman correlation and the model fit with a random publication date (**Suppl. Fig. S1**). To assess the impact of dating imprecision on the results, the data were submitted to 1,000 surrogations with random temporal jitter of 100 years, or the difference between the oldest and newest estimated dates, whenever that difference was larger than 100 years (**Suppl. Fig. S2**).

3. RESULTS & DISCUSSION

3.1. Historical dynamics of discourse structure

We assessed whether the historical development of graph attributes in texts from ~2,500 BC to 2,014 AC structurally resembles the ontogenetic dynamics of the same attributes in oral reports (Fig. 2**A**). For standardization, the analyses were performed for texts in English. Mimicking the ontogenetic pattern [9], lexical diversity, graph length and long-range recurrence increased steadily over time across different traditions, while short-range recurrence decreased (Fig. 2**B; Table 2**). Using 2,500 BC as the most parsimonious estimation of t = 0 for the birth of written culture (Table 1), the literary data were remarkably well fit by the same model that described the ontogenetic data in typical participants [9] (Fig. 2**B**). The null hypothesis of lack of temporal structure in the data was refuted by the same surrogation procedure described above (**Suppl. Fig. S1**). As expected, f_∞ - f_0 was positive for all graph attributes except RE, which was negative (Table 2).

Research on literary data entails assessing data points that are not independent, since books are linked by multiple cultural influences. To avoid overestimating statistical power, we nested the data by literary tradition, and exponentially fitted the mean weighted by the standard error of the graph attributes in each tradition. The nested data showed the same overall dynamics observed for all texts (Fig. 2**C**), with almost no differences in characteristic time (T) for N (5,321 AC for all data; 5,120 AC for nested data), an approximation of T to the upper and lower boundaries of the Axial Age onset for RE (1,127 BC for all data; 603 BC for nested data) and LSC (1,427 BC for all data; 731 BC for nested data), and an anticipation of future saturation for ASP (96,946 AC for all data; 44,482 AC for nested data) (Table 2).

Table. 2
Parameters for Spearman and exponential correlations of graph attributes with historical time (all and nested data by literary tradition - fit of mean graph attributes weighted by standard error). Bonferroni correction for 4 comparisons, α = 0.0125. Before and after Christ's birth, respectively BC and AC. Note that the characteristic times for RE and LSC (603 BC and 731 BC) occur near the onset of the Axial Age.

Spearman	**N**	**RE**	**LSC**	**ASP**
Rho	0.50	-0.46	0.49	0.54
p	4.18E-30	1.23E-24	5.97E-28	6.23E-35
Goodness (all data)	**N**	**RE**	**LSC**	**ASP**
R^2	0.24	0.23	0.42	0.30
SSE	564.74	125.51	3243.73	70.66
RMSE	1.13	0.53	2.70	0.40
Asymptotic f_∞	30.00	0.09	19.34	29.00
Characteristic time *T* (years)	5,321 AC	1,127 BC	1,427 BC	96,946 AC
Coefficient f_0	22.34	2.55	1.00	3.66
Goodness (nested data)	**N**	**RE**	**LSC**	**ASP**
R^2	0.46	0.56	0.71	0.49
SSE	1160.61	163.78	6231.67	153.10
RMSE	13.91	5.22	32.23	5.05
Asymptotic f_∞	30.00	0.00	21.44	16.20
Characteristic time *T* (years)	5,120 AC	603 BC	731 BC	44,482 AC
Coefficient f_0	21.99	2.52	1.00	3.57

For text analysis across multiple live and dead languages and alphabets, this approach has the caveat of the need to use translations, mitigated here by the use of a single target language (English), and by the translation robustness of the differential diagnosis of psychosis based on graph analysis, which is nearly invariant across five major European languages including English [19]. To further investigate translation as a potential source of noise, transliterated original texts were subjected to graph analysis for comparison with their English translations (**Suppl. Table S1**). Significant positive correlations were observed for N, RE and ASP (**Suppl. Fig. S3A**), but LSC showed no correlation due to a subset of Bronze Age texts with substantially larger LSC in the English translations than in the originals (**Suppl. Fig. S3A**). As a consequence, the abrupt LSC increase at the Axial Age onset is even more marked in originals than in translations (**Suppl. Fig. S3B**). Overall, the dynamics of graph attributes in the original texts agrees with the results obtained for the larger sample of translated texts.

While the earliest texts show near-random long-range recurrence, later texts depart progressively from randomness. In contrast, short-range recurrence is much above random in the earliest texts, and becomes sub-random in the later ones. This is clear in a 2D plot of LSC and RE normalized by mean random values, which reconstitutes the temporal dynamics of the data based solely on structural properties (Fig. 3**A**). Indeed, almost 40% of the time variance among texts is explained by a single scalar combining normalized LSC and RE (Fig. 3**B**). A particularly interesting case is that of Hinduist literature, which evolved across 2,750 years from a primitive pattern of near-random long-range recurrence to measurements quite far from random (Fig. 3**C**).

The exponentially saturating fits yielded characteristic times for the dynamics of graph attributes in literature (Table 2). The results indicate that the structure of written discourse began to mature much after the earliest record. For 'all data' and 'nested data', LSC showed characteristic times of 1,427 BC and 731 BC, respectively. For RE these times were 1,127 BC and 603 BC, respectively. This means that LSC and RE began to mature between the Middle/Late Bronze Age and the onset of the Axial Age. Interestingly, the saturation of lexical diversity and graph length is estimated to be in the distant future for "all data" and "nested data", respectively: 5,321 AC and 5,120 AC for N; 96,946 AC and 44,482 AC for ASP.

Unintended bias in the reference sample is a potential caveat: while our selection of classical texts is quite comprehensive, the sampling becomes increasingly arbitrary due to book popularization following

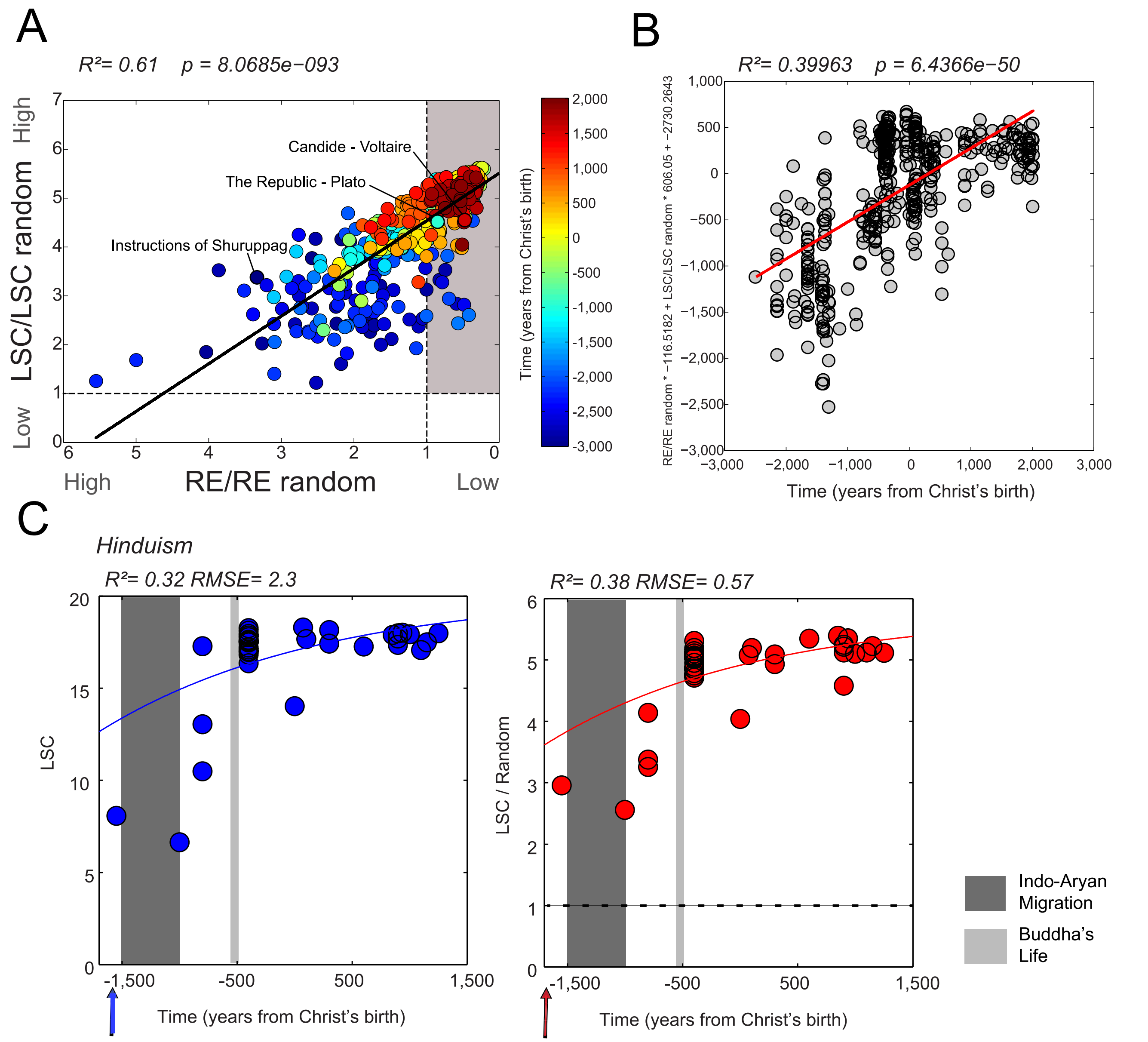

Figure. 3. The maturation of literary structure reflects historical time. All texts translated to English. **(A)** LSC and RE normalized by mean random values reconstitute the "arrow of time". Grey rectangle indicates supra-random LSC and infra-random RE (R^2 and p values of Pearson correlation between the two normalized attributes indicated on the top). **(B)** A linear combination of normalized LSC and RE strongly correlates with historical time (R^2 and p values of multiple linear regression using least squares indicated on the top, coefficients for each attribute indicated on the y axis). **(C)** LSC saturates over time in Hinduist literature, with characteristic times near the Indo-Aryan migration [63]. R^2 and root-mean-square error (*RMSE*) indicated on top. For information about the model and parameters used, see Method and **Table 1**.

Gutenberg's printing press ~1,440 AC. To address this problem, 10 randomly-sampled sets of 20 Postmedieval texts [28] were analyzed and their graph attributes do not differ significantly from those of the reference sample (**Suppl. Fig. S3C**). Another caveat that requires attention is the intrinsic noise due to dating errors, which increase as we move towards the past. The criteria of "middle of author's life" and "middle of historical period" were employed to parsimoniously and systematically address dating uncertainties regarding exact date of publication or authorship. To assess the effects of possible dating errors derived from these criteria, each data point was randomly subjected to a jitter of 100 years (on the high end of human longevity), or to a jitter equal to the difference between the oldest and newest estimated dates, whenever that difference was larger than 100 years. Exponential fit parameters for 1,000 such data jitterings did not differ significantly from the values estimated above, indicating that dating errors are unlikely to mislead the interpretation of the data (**Suppl. Fig. S2**).

3.2. Written structure converged abruptly to contemporary educated adult levels at the onset of the Axial Age

Inferring the ancient mind based on a mathematical analysis of arcane records has an inevitable degree of speculation, but cognitive archeology gains depth when ancient literary data are compared to extant psychological data. The structural dynamics of historical texts shows similarity to the dynamics observed in typical literate participants, and most Bronze Age texts have graph attributes comparable to those measured in present-day reports from adults with psychotic symptoms or typically-developing children. One way to interpret the data is to consider that ancient literature resembles psychotic speech. Another is to conclude that ancient written discourse is structurally comparable to oral reports of present-day children. Both interpretations resonate with the notion that adult psychosis reflects childish residues [46]. This is likely related to developmental limitations in working memory and attention [47], which subside with education [48]. Not surprisingly, these limitations are also observed in patients with psychotic symptoms [49].

But the structural resemblance of childish, psychotic and ancient discourses does not necessarily imply similar mental functioning. Ancient texts were often a repository for the oral recitation of poetry—hence their repetitive structure. Rather than being psychotic or puerile, perhaps the ancient peoples simply wrote like poets. Alternatively, it is conceivable that the structure of ancient texts is simply too quaint to be meaningfully compared to the cultural record of extant literate societies, i.e. perhaps Bronze Age discourses are similar to narratives from preliterate societies or individuals.

To address the first possibility, we compared the data to Postmedieval Western poetry (N = 60) [28]. To address the second possibility, we assessed oral reports from three illiterate groups characterized by a decreasing gradient of indirect exposure to written discourse: illiterate adults (N = 18) and preschool children (N = 18) [9], as well as non-literate Amerindians (N = 41 reports from at least 12 different narrators) [28]. As expected, there was an orderly structural gradient across groups (**Fig. 4A,B**). Importantly, Bronze Age texts differ significantly from poetry as well as preliterate narratives from either Amerindian adults or preschool children, but not from illiterate adults (**Table 3**). Interestingly, poetry mixed features from preliterate narratives (small LSC leading to reduced graph length) and contemporary literature (larger lexical diversity and fewer short-range recurrences, in comparison with both Pre and Postaxial texts).

From a strictly structural point of view, cultural accumulation allowed for changes across 2.5 millennia that in typical children take ~12 years of schooling. Surely Plato's writings were no adolescent material, being manifestly interested in adult topics. Still, Plato's writings and other Axial classics are at par in structural complexity with modern-day oral reports from typical participants above 12 years old: far from typical children and individuals with psychotic symptoms, and much closer to Voltaire than to Shuruppag (**Fig. 3A**).

Childish or psychotic as it may, the ancient textual record reached a structural plateau around 800 BC, as shown by a moving window averaging of the data across all nine traditions (**Fig. 5A-D**). The four graph attributes show highly significant changes between the Bronze Age and the Axial Age (**Table 4**). This sharp empirical transition, as well as the characteristic times for RE (1,127 BC for 'all data', 603 BC for 'nested data') and LSC (1,427 BC and 731 BC, respectively), agrees well with the cultural collapse between the end of the Bronze Age (~1,200-1,000 BC) and the onset of the Axial Age (~800 BC), when droughts, famine, plagues, war, invasions and natural cataclysms led to social disorganization, educational disruption, and literacy reduction [50]. Interestingly, this transition represented a departure from near-random long-range structures (N, LSC and ASP), with the opposite happening in the short-range (RE) (**Fig. 2D,** top panel).

4. CONCLUSIONS

The use of nonsemantic word graphs to describe structural changes in the written discourse revealed major change across the entire historical record. Starting from the earliest stage when literature was closely linked to recitation and used schemes typical of orality, such as repetition, texts asymptotically matured into having richer vocabularies, less repetition, and more long-range structure. These results resemble the effects of education on the speech structure of typical adults [9].

Before the invention of writing, the ability to narrate real or fictional events was nearly exclusively mediated by oral storytelling, aided by gestural and postural communication. Short-range recurrence was likely favored because it facilitates rhyme and rhythm, as well as the memorization of short strings of words [51]. The need for attentive recall and the taste for reiteration is emphatically expressed in the words of the last king of the Sumerian city-state of Shuruppag in one of the earliest extant texts, possibly dating from before 2,500 BC: *"In those days, in those far remote days, in those nights, in those faraway nights, in those years, in those far remote years, at that time the wise one who knew how to speak in elaborate words lived in the Land; Shuruppag, the wise one, who knew how to speak with elaborate words lived in the Land. Shuruppag gave instructions to his son; Shuruppag, the son of UbaraTutu gave instructions to his son Ziudsura: My son, let me give you instructions: you should pay attention! Ziudsura, let me speak a word to you: you should pay attention!"* [52].

However, a highly recursive structure hinders the communication of complex meaning, which requires long-range semantic context and imagetic schema [53], but is disrupted by short cycles [54]. Load restrictions on attention and working memory [55] must have limited the structural complexification of narratives for millennia. As noted by Plato [56], the invention of written text as an external support for memory allowed for a substantial increase in the size and complexity of the narratives, no longer constrained by the needs and strategies of memorization. This transformation seems to be well captured by our analysis. Ancient literature became structurally more complex as it developed, with an increase over time in the diversity of words employed, fewer repetitions of short-range word sequences and increasingly larger connected components. In particular, the dynamics of recurrence is characterized by a monotonic increase in range, likely reflecting the departure from oral to written discourse, the former strictly dependent on working memory, the latter much less so.

Despite the indirect exposure to written discourse, illiterate adult participants display a Bronze Age pattern: Although they have been immersed for a long time in the literate culture, full literacy never developed. Reports from preschool children, while similar to Bronze Age literature in LSC and RE, have significantly smaller graphs and less lexical diversity, denoting little exposure to the literate culture. The Amerindian reports, although comprising elaborate oral narratives that take long years of training to be properly memorized in shape and content [34], were fart in structure from Bronze Age texts.

The sharp transient in graph attributes ~800 BC supports the notion of an Axial Age [23], which has been challenged as a vague concept without empirical evidence [24,25,27], or as a fuzzy period void of a precise geotemporal determination [57,58]. However, a quantitative semantic analysis of Judeo-Christian and Greco-Roman texts detected increased text similarity to the concept of "introspection" throughout the Axial Age [26]. Statistical modeling attributed the timing of the Axial Age to economic development, not political complexity nor population size [27]. This has been interpreted as evidence that the intellectual blossoming of the Axial Age derived from changes in reward systems, rather than from changes in cognitive styles [25,27]. Our results argue for a complementary view: The economical prosperity of the Axial Age co-existed with a major change in discourse structure, with a contemporary parallel in the maturation of oral reports that depends more on years of education than on biological age [9].

Bronze Age texts are structurally similar to oral reports from both literate children and adult psychotic participants [9]. The notion that psychosis resembles childish or primitive behavior is culturally pervasive, but so far has lacked empirical support. While the graph-theoretical similarity of Bronze Age literature and psychotic discourse is compatible with the notion that Bronze Age mentality was psychotic-like [22], it surely does not imply that the graph-theoretical features of oral and written discourse produced by psychotic participants, literate children and ancient authors had similar underlying causes. Despite the formal similarities reported here, the mechanisms responsible for the changes from childhood to adulthood and in psychosis are likely to differ.

Our results also indicate that Amerindian discourse is even more distant in structure from Bronze Age literature. Amerindian narratives

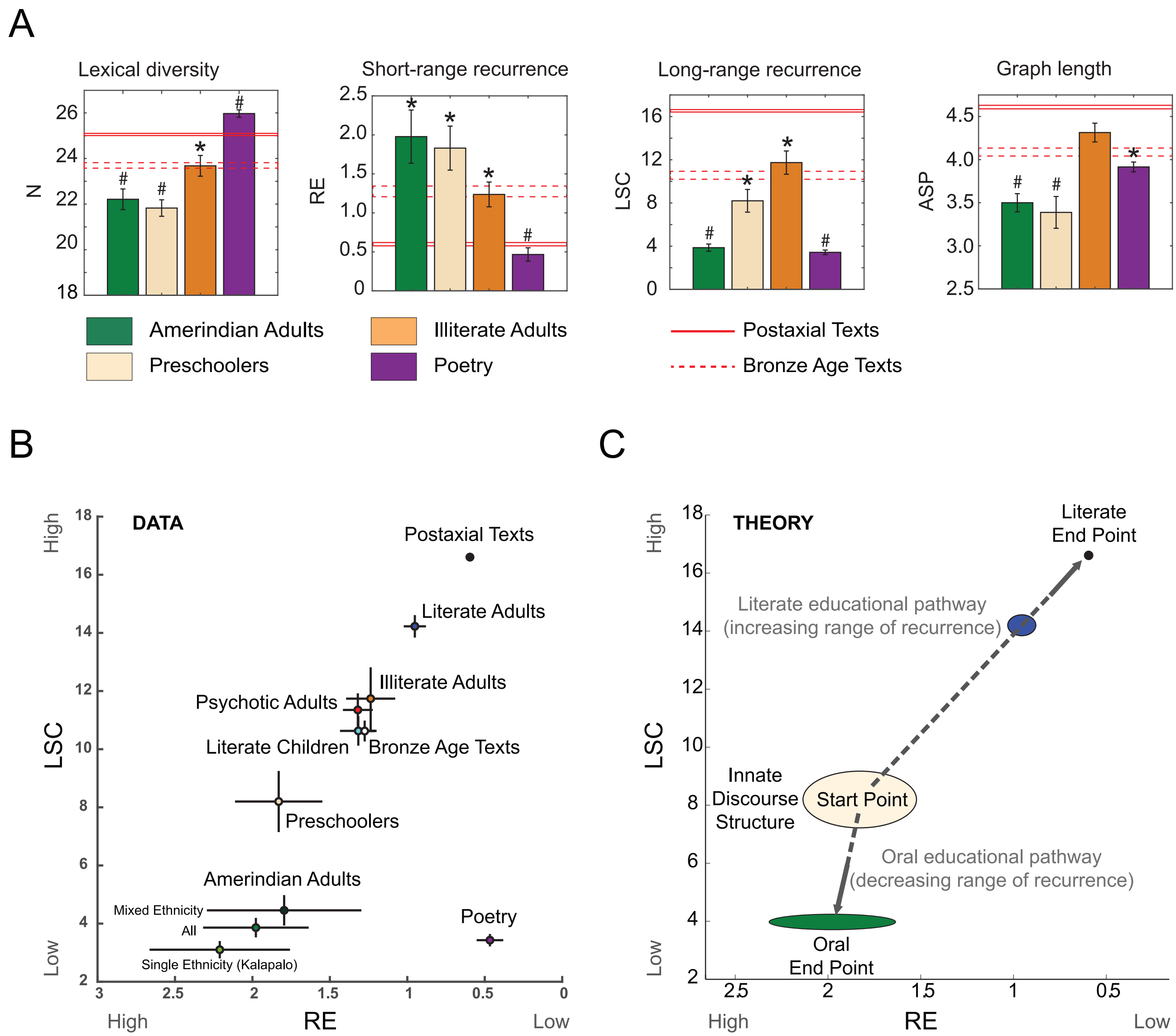

Figure. 4. Graph attributes from Bronze Age texts differ from the graph attributes of Poetry and preliterate narratives from Amerindian adults or urban preschoolers. (A) $M \pm SEM$ for each graph attribute of interest. * indicates differences from Postaxial texts and # indicates differences from both Bronze Age and Postaxial texts, with $p < 0.05$ corrected for multiple comparisons (Wilcoxon rank sum test, two-tailed, Bonferroni correction for 32 comparisons, $\alpha = 0.0016$; p values in Table 3). Dashed and solid red lines indicate the boundaries given by $M \pm SEM$ of Bronze Age and Postaxial texts, respectively. Bronze Age texts did not differ significantly from oral reports from illiterate adults in any structural measure. In contrast, Bronze Age texts did not differ from Poetry only for ASP, from narratives from Amerindian adults only for RE, and from oral reports from preschool children for RE and LSC. Overall, Bronze Age texts showed more structural differences than similarities with Poetry or Amerindian narratives. (B) $M \pm SEM$ for LSC versus RE. Note that Poetry and Amerindian narratives have very distinct structures. (C) Education seems to produce opposite effects on the structure of discourse in literate versus oral traditions, so that the range of recurrence increases in the former (i.e. low RE but high LSC), and decreases in the latter (i.e. high RE but low LSC). This theoretical scheme assumes that Amerindian children would display the same innate structural start point as urban preschoolers, a supposition that is reasonable but that remains to be empirically verified.

often take many years of training to be learned. Recitation is accompanied by complex sequences of gestures and postures, and in some traditions tends to maintain a very similar structure across different narrators [34]. Short-range recurrence is pervasive, and the several forms of parallelism used in such oral performances indicate that the repetition of words or sentences is an important feature of a highly regarded style of both thinking and narrating [34]. If, on one hand, writing presents new possibilities for narrative complexity, it also limits certain characteristics of thought which, in societies without writing or that were developing writing millennia ago, are/were valued and considered functional. The data suggest that the educational pathways of oral and literate traditions diverge at the structural level, with a decreasing range of recurrence in the former, and an increasing range of recurrence in the latter (Fig. 4C).

A comparison of the characteristic times for the historical development of graph attributes (Fig. 2D, top panel) with corresponding times across ontogenetic development (Fig. 2D, bottom panel, previously measured in [9]), shows that education-related cultural accumulation makes discourse less recursive and more connected at both the historical and ontogenetic levels. Yet, the corresponding transformation paths are only partially overlapping. While the monotonic dynamics in both are overall quite similar, the temporal order of saturation for specific graph attributes differs.

Historically, the earliest maturation of discourse structure occurred for the increase in long-range recurrence and decrease in short-range recurrence between the Middle/Late Bronze Age and the Axial Age. Thus, discourse structure matures by increasing the range of recurrence. Similarly to the ontogenetic data [9], a decrease in short-range

Table. 3
Statistically significant differences between Bronze Age and Postaxial texts comprising Poetry and oral reports from Illiterate Adults, Preschool children and Amerindian adults. Significant *p* values indicated in bold (Bonferroni correction for 32 comparisons, $\alpha = 0.0016$).

Wilcoxon Ranksum test (*p* values)	N	RE	LSC	ASP
Bronze Age x Amerindian adults	**0.0002**	0.0837	**<0.0001**	**<0.0001**
Postaxial x Amerindian adults	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Bronze Age x Preschool children	**<0.0001**	0.0819	0.0380	**<0.0001**
Postaxial x Preschool children	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Bronze Age x Illiterate adults	0.9397	0.9240	0.1107	0.0527
Postaxial x Illiterate adults	**0.0002**	**<0.0001**	**<0.0001**	0.0088
Bronze Age x Poetry	**<0.0001**	**<0.0001**	**<0.0001**	0.0507
Postaxial x Poetry	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**

recurrence is an early marker of maturation in literature. However, lexical diversity and graph length follow a distinct path, not stabilizing until much beyond the present. These differences are likely related to the fact that the historical data was not produced by children, but by educated adults of the cultural elites of yore. The historical and ontogenetic paths differ, but reach similar outcomes.

Table. 4
Statistically significant differences between historical periods (Early and Middle/Late Bronze Age, Axial Age and Postaxial Age). Significant *p* values indicated in boldface (Bonferroni correction for 24 comparisons, $\alpha = 0.0021$).

Wilcoxon Ranksum test (*p* values)	N	RE	LSC	ASP
Middle/Late Bronze x Axial	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Early Bronze x Middle/Late Bronze	**0.0000**	0.0158	0.0144	**0.0010**
Early Bronze x Axial	0.5839	0.2141	**<0.0001**	0.0976
Middle/Late Bronze x Postaxial	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Axial x Postaxial	0.0040	0.0255	0.6257	**0.0011**
Early Bronze x Postaxial	0.0753	0.0299	**<0.0001**	**0.0010**

Nowadays as well as during the Bronze Age, learning to read and write requires the overcoming of major neural barriers related to ancestral evolutionary constraints, such as symmetric face-recognition in the fusiform gyrus [59], which becomes specialized for letter and word recognition upon literacy acquisition [2, 60, 61]. More often than not, students as well as teachers lack key knowledge of the development of the phonological system, phoneme-grapheme mapping, and the higher-order language processes required for reading and writing [2,13]. While learning to read and write depends to a large extent on parental background, core language abilities and prereading skills [14], effective

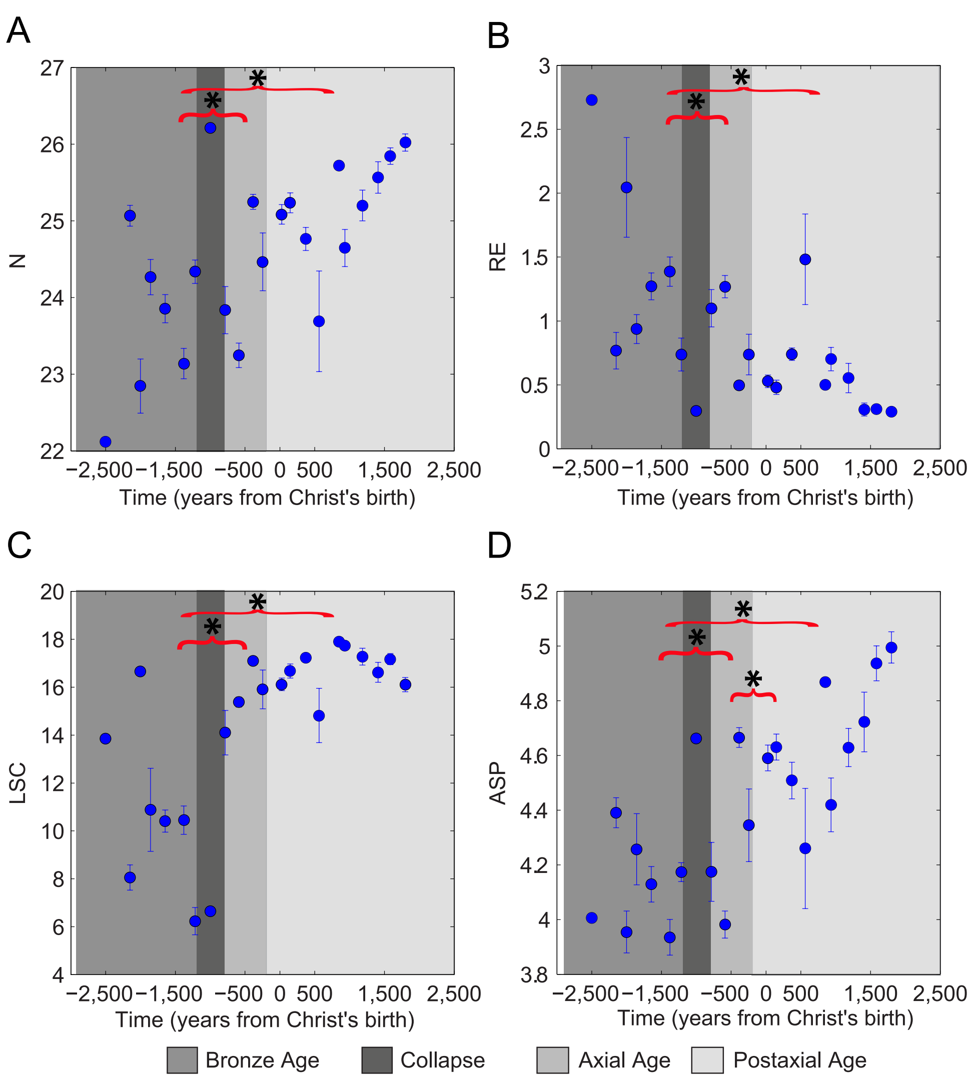

Figure. 5. Empirical transition in text structure near the onset of the Axial Age. Marked transient in graph attributes across all traditions for **(A)** N, **(B)** RE, **(C)** LSC, and **(D)** ASP. Plotted are non-overlapping moving averages (windows of 200 years, *M* ± *SEM*). The * indicates $p < 0.05$ corrected for multiple comparisons, *p* values in Table 4 (Wilcoxon rank sum test, two-tailed, Bonferroni correction for 24 comparisons, $\alpha = 0.0021$). All texts translated to English.

school pedagogy can have a major impact on learning [62]. Despite all the ontogenetic and historical 'noise', education seems to shape the graph-theoretical landmarks so as to conquer in less than two decades advances comparable to the past five millennia. The results imply that, at any given time, it is the educated individual able to create literature – the writer – who will push the envelope of discourse structure.

5. FUNDING

Work supported by UFRN, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), grants Universal 480053/2013-8, 425329/2018-6 and 408145/2016-1 and Research Productivity 308775/2015-5 and 301744/2018-1; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Projects OBEDUC-ACERTA 0898/2013, PROEX 534/2018 Grant No. 23038.003382/2018-39 and STIC AmSud 062/2015; Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco (FACEPE) Grant No. APQ-0642-1.05/18; this article was produced as part of the activities of FAPESP Center for Neuromathematics (grant #2013/07699-0, S. Paulo Research Foundation), Boehringer-Ingelheim International GmbH (grants 270561 and 270906).

6. Ethics

Our submission has not been previously published, is not submitted for publication elsewhere, and has been deposited as a preliminary version at arXiv:1612.09268 [q-bio.NC]. This study used data from two protocols approved by the Research Ethics Committee of the Federal University of Rio Grande do Norte (permits #102/06-98244 and #742.116). Signed informed consent was obtained from all participants and also from a legal guardian when necessary, and the study adhered to all relevant ethical regulations. The exclusion criteria were any neurological condition or alcohol/drug abuse. Literary textual sources included the Digital Egypt of the University College London (http://www.ucl.ac.uk/museums-static/digitalegypt/), the Electronic Text Corpus of Sumerian Literature of the University of Oxford (http://etcsl.orinst.ox.ac.uk/), Project Gutenberg (www.gutenberg.org), and The Internet Classics Archive of the Massachusetts Institute of Technology (http://classics.mit.edu/). Amerindian oral narratives were obtained from one of the authors (AG) under permit 1712/09 from the National Indian Foundation (FUNAI), from a public corpus at the University of Campinas (http://www.tycho.iel.unicamp.br/corpus/), from a public corpus at the University of Texas (https://ailla.utexas.org/), and from publications.

Declaration of Competing Interest

The authors declare no competing interests.

ACKNOWLEDGEMENTS

We thank the Hospitals “Onofre Lopes” and “João Machado”, and mental health clinic “CAPS Infantil”, for the sampling of psychiatric patients; the Schools “Arte de Nascer”, “Ulisses Góis”, “Antonio Severiano”, “Carlos Belo Moreno", “Luis Antonio”, “Arnaldo Monteiro Bezerra”, and “Berilo Wanderley” for the sampling of school students; M Posner, S Dehaene, S Bunge, CJ Cela Conde, C Gilbert, S Lipina, D Araujo, C Queiroz, J Sitt, JV Lisboa, A Cabana, J Queiroz, A Battro, J Luban, MP de Souza, M Leite and P Dalgalarrondo for insightful discussions and comments on the manuscript; M Laub and JE Agualusa for source material; PPC Maia and S Morais for IT support; D Koshiyama, I Pereira and V Tollendal for documentation support; AEA Oliveira for help with the sampling of illiterate adults sample; Instituto Metrópole Digital and the High Performance Computing Center at UFRN (NPAD/UFRN).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tine.2020.100142.

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