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Abstract

This study is concerned with the question how endogenous eye movement dynamics change as they become contingent on external (linguistic) information. It is hypothesized that external information lead to increased sequential order of eye movement measures, compared to conditions that contain little or no information. To test this hypothesis, eye movements of 26 German native speakers were recorded during reading-unrelated and reading-related tasks. To analyze the data, we used recurrence quantification analysis (RQA), which quantifies the degree of temporal structure in time series. Recurrence measures of eye movements convincingly distinguish between conditions. Findings suggest that qualitatively different tasks can be measured on a continuum of temporal structure and provide new perspectives for further studies investigating natural reading as complex, dynamical process.

Keywords: text reading, nonlinear dynamics, information processing, recurrence quantification analysis, reading time regularity

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How can we quantify the coupling between a text and reading performance? The hypothesis of reading time regularity (RTR) states that the degree of regularity in measures of the reading process (e.g., reading times or eye movements) can serve as a proxy for coupling between cognitive processes and (linguistic) task information, and hence is informative about reading fluency and comprehension. RTR captures the extent to which relevant linguistic information of a text controls its perceptual-cognitive processing during reading (Wallot, 2014, 2016). The current study provides a test for the basic assumption of the hypothesis, namely, that eye movement fluctuations contingent on linguistic information differ in their temporal structure from endogenous fluctuations of eye movements that are not contingent on external information.

Method

The methods described below were approved by the Ethics Council of the Max Planck Society.

Participants

26 native speakers of German with normal or corrected-to-normal vision participated in the study. They received a compensation of 15 € each. One participant terminated the experiment before completion. Due to technical problems during calibration procedure and data recording, data of two participants was excluded. Additionally, data of one participant was excluded as in two conditions more than half of the items had to be discarded due to excessive artifacts and blinks. Thus, the final sample consisted of 22 participants (13 female) with a mean age of 30.76 years (*SD* = 11.48).

Materials

The study was composed of six distinct conditions, three of which were unrelated to language, another two reflecting certain aspects of the reading process, and the final one consisting of normal text reading. The language-unrelated conditions serve as 'baselines' for eye movements in the absence of external (linguistic) information. These baseline conditions consisted of looking at a fixation cross, a blank screen, and a random pattern of circles. The reading conditions were selected to reflect different degrees of available linguistic information. First, participants were asked to look at x-sequences that reveal certain surface characteristics (e.g., word length), but lack any semantic access. Another condition consisted of scrambled text allowing participants to process local word semantics, but preventing in-depth processing. Finally, participants were asked to read actual texts composed from newspaper articles.

Each condition consisted of seven trials. Fourteen newspaper articles were selected and randomly arranged in two lists. From each newspaper article, one version consisting of x-sequences and one scrambled text version was derived. If list A contained the actual newspaper article, then the other two versions of the text were assigned to list B and vice versa.

Procedure

Prior to the experiment, written informed consent was obtained from all participants. An EyeLink 1000 (SR-Research) was used for monocular data recording of the left eye at a sampling rate of 1000 Hz. Before any data was recorded, a 12-point calibration in random sequence and a subsequent validation were executed. Participants were evenly assigned to either of the two lists differing in texts. Experimental trials were displayed in a randomized order. A fixed presentation duration of 60 seconds was set for fixation cross, blank screen, and random circles conditions. Subjects proceeded in a self-paced manner for x-sequences, scrambled text, and text conditions.

Data Analysis

Blinks were detected by an algorithm based on pupillometry noise (Hershman et al., 2018) and removed from the data. As dependent variables, gaze steps were computed by differencing the raw 2D-position data (Stephen, & Mirman, 2010). Furthermore, fixation times for trials of the reading conditions were extracted from the data using the Microsaccade Toolbox for R (Engbert et al., 2015). Subsequently, both measures were subjected to recurrence quantification analysis (RQA; Webber, & Zbilut, 1994, Zbilut & Webber, 1992) using the crqa package for R (Coco et al., 2020). RQA can be used to quantify various dynamic properties of a time series related to the degree of randomness and structure of its temporal evolution. It can be visualized by means of recurrence plots (RP) based on which several complexity measures can be derived quantifying the density of recurrence points and their line structures (Marwan et al., 2007, Wallot, 2017).

Several RQA measures can be extracted from an RP, but we will focus on the following ones: The recurrence rate (RR) refers to the density of recurrence points, providing information about the repetitiveness of states within the timeseries. The less stochastic and the more deterministic a process is, the more recurrent points occur in connected trajectories as opposed to single recurrence points. How many recurrent points occur in diagonal lines as opposed to individual repetitions is indicated by determinism rate (DET). The line length can also be extracted, either as average diagonal line length (ADL) or as maximum diagonal line length (MDL; Coco et al., 2020, Marwan et al., 2007).

Before running RQA, a delay parameter τ, and an embedding parameter D have to be estimated, e.g., by computing the average mutual information, and false nearest neighbor functions. Z-scored data will then be subjected to RQA. Following suggestions from Wallot (2017), a threshold parameter T will be chosen by an iterative procedure resulting in a mean RR between 5 and 10 percent across the whole sample of trials and participants. Linear mixed-effects models were set up using the lme4 package (https://cran.r-project.org/package=lme4), and tested for statistical significance using the lmerTest package (https://cran.r-project.org/package=lmerTest) for R.

Hypotheses

Drawing on the hypothesis of reading time regularity (RTR), it is predicted that the presence of external and relevant linguistic information increases the coupling between cognitive processing and the sequential structure of that information, which becomes apparent in the temporal structure of eye movement measures. That is to say, eye movement dynamics become more systematic over time.

Since we have no theoretical grounds to expect the three baseline conditions to differ regarding information content, we do not hypothesize particular differences among them. However, we expect the three reading conditions to exhibit more temporal eye movement structure compared to these baseline conditions. While the x-sequence condition resembles the sequential visual layout of a natural text, the scrambled text condition lacks this ordering, but contains the individual word semantics. We have no particular prediction about which of these factors will exert a stronger influence on recurrence measures of eye movements, but we hypothesize that both will show less temporal structure compared to the natural text condition.

Finally, we will examine differences between the three reading conditions using time series of fixations, not gaze step, expecting again that the natural text condition will exhibit the strongest degree of temporal regularity. Fixation durations were only used to compare the reading conditions, because the baseline conditions produced mostly drift-like eye movements, which are not well captured as fixations and saccades.

Results

For the gaze step data, the following parameters were chosen: $\tau = 7$, $D = 7$, $T = 0.3$ ($M_{\text{RR}} = 7.50$, $SD_{\text{RR}} = 5.93$). We constructed a linear model for each RQA measure as a function of experimental condition with participants as a random effect, as well as random intercepts. As shown in Table 1, all four complexity measures distinguish most significantly between reading and baseline conditions: The baseline conditions exhibit smaller RR, DET, ADL, and MDL. However, differentiation of the reading conditions is less obvious. While x-sequences and scrambled text conditions show quite distinct patterns, normal text lies in between.

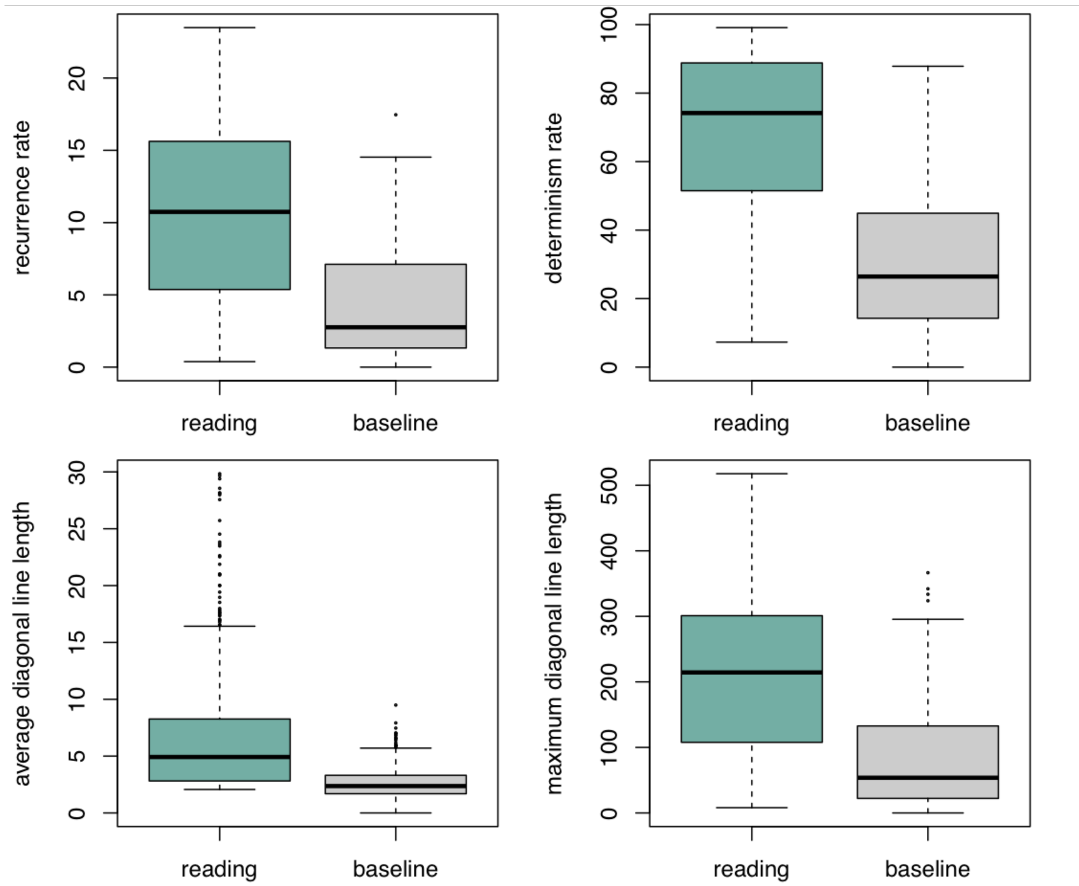
Table 1

Statistical Significance of RQA Measures: Gaze Step

Measure	Contrast	Estimate	*SE*	*df*	*t*	*p*	
RR	reading vs. baseline conditions	-6.57	0.19	876.04	-34.23	<0.001	***
	text vs. x-sequences and scrambled text	-0.05	0.29	875.01	-0.16	0.874	
	text vs. x-sequences	-0.78	0.51	875.02	-1.52	0.128	
	text vs. scrambled text	0.39	0.72	874.99	0.55	0.583	
	x-sequences vs. scrambled text	1.89	0.71	876.01	2.64	0.008	**
DET	reading vs. baseline conditions	-37.7	0.90	876.03	-41.82	<0.001	***
	text vs. x-sequences and scrambled text	-0.50	1.37	875.00	-0.37	0.712	
	text vs. x-sequences	-6.84	2.72	874.99	-2.52	0.012	*
	text vs. scrambled text	0.20	3.81	874.95	0.05	0.958	
	x-sequences vs. scrambled text	15.05	3.78	875.97	3.98	<0.001	***
ADL	reading vs. baseline conditions	-4.61	0.22	876.11	-20.52	<0.001	***
	text vs. x-sequences and scrambled text	0.13	0.34	875.04	0.39	0.693	
	text vs. x-sequences	-0.19	0.48	875.06	-0.39	0.696	
	text vs. scrambled text	-1.59	0.67	875.03	-2.38	0.017	*
	x-sequences vs. scrambled text	2.20	0.66	876.05	3.31	<0.001	***
MDL	reading vs. baseline conditions	-126.83	3.78	876.03	-33.52	<0.001	***
	text vs. x-sequences and scrambled text	-1.49	5.74	875.01	-0.26	0.795	
	text vs. x-sequences	-13.19	9.98	875.02	-1.32	0.186	
	text vs. scrambled text	4.77	13.98	0.34	0.733	0.733	
	x-sequences vs. scrambled text	34.07	13.92	876.01	2.45	0.014	*

Figure 2

RQA Measures: Gaze Step



For fixation durations, the following parameters were chosen: $\tau = 2$, $D = 3$, $T = 0.8$ ($M_{RR} = 7.57$, $SD_{RR} = 4.21$). Again, linear models for each RQA measure were constructed with experimental condition as fixed effect and participants as a random effect and random intercepts. As is apparent in Table 2, x-sequences and scrambled text differ most significantly regarding DET, ADL, and MDL with scrambled text indicating less DET, on average longer diagonal lines, but shorter MDL. Both conditions are not distinguishable by means of RR. Normal text and x-sequences show highly significant differences regarding ADL, and MDL, while RR and DET are similar. However, the opposite pattern occurs when normal text and scrambled text are compared: While normal reading results in a higher RR and DET, line length measures are similar.

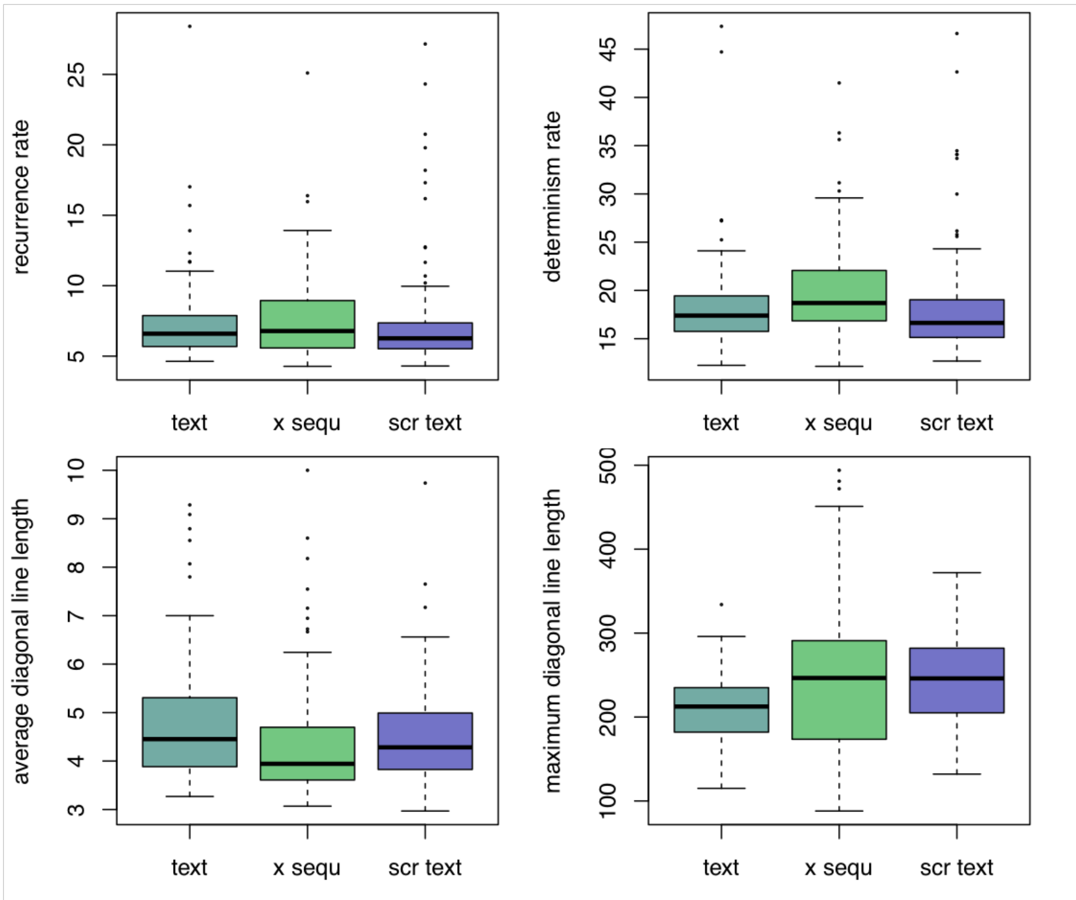
Table 2

Statistical Significance of RQA Measures: Fixation Duration

Measure	Contrast	Estimate	*SE*	*df*	*t*	*p*	
RR	text vs. x-sequences and scrambled text	-0.57	0.36	439.00	-1.58	0.113	
	text vs. x-sequences	-0.20	0.42	438.00	-0.48	0.633	
	text vs. scrambled text	-0.95	0.42	438.00	-2.27	0.023	*
	x-sequences vs. scrambled text	-0.75	0.42	439.00	-1.79	0.074	
DET	text vs. x-sequences and scrambled text	-1.28	0.47	439.00	-2.70	0.007	**
	text vs. x-sequences	-0.22	0.54	438.00	-0.41	0.682	
	text vs. scrambled text	-2.34	0.54	438.00	-4.35	<0.001	***
	x-sequences vs. scrambled text	-2.12	0.54	439.00	-3.91	<0.001	***
ADL	text vs. x-sequences and scrambled text	18.55	6.75	439.00	2.75	0.006	**
	text vs. x-sequences	-0.32	0.12	438.00	-2.67	0.008	**
	text vs. scrambled text	0.11	0.12	438.00	0.91	0.365	
	x-sequences vs. scrambled text	0.43	0.12	439.00	3.57	<0.001	***
MDL	text vs. x-sequences and scrambled text	-0.11	0.11	439.00	-1.00	0.316	
	text vs. x-sequences	38.31	7.57	438.00	5.06	<0.001	***
	text vs. scrambled text	-1.21	7.57	438.00	-0.16	0.873	
	x-sequences vs. scrambled text	-39.51	7.63	439.00	-5.18	<0.001	***

Figure 2

RQA Measures: Fixation Duration



Discussion

The results show that recurrence measures of gaze step data differentiate between baseline and reading conditions in our study. All investigated complexity measures were less pronounced for the 'baseline' conditions. This clearly indicates that linguistic information, no matter the extent, leads to a more deterministic structure guiding our eye movements. Differences among the reading conditions were not so clear when examining gaze step. However, recurrence measures of fixation times can distinguish between the different degrees of information within the three reading conditions of our experiment. Compared to encoding x-sequences, normal reading results in shorter ADL, but longer MDL. In contrast to reading scrambled text, normal reading exhibits higher RR and DET.

These findings provide first evidence for the RTR hypothesis, showing that eye movement fluctuations during text reading differ systematically in the strength and degree of temporal structure compared to baseline conditions that putatively capture endogenous fluctuations of eye movements in the absence of (linguistic) information. Moreover, they show how qualitatively different tasks (such as staring on a fixed location and reading text) can be meaningfully measured on a continuum of temporal structure, even though contrasts among the reading conditions are more sensitive examining fixation time series.

Overall, these findings provide a new and important perspective for further studies investigating natural reading as complex, dynamical process using measures of temporal structure. Particularly, they suggest that the coupling between cognitive processes during reading and the underlying linguistic information can be captured by examining the temporal properties of eye movements.

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