Power-law fluctuations in eye movements predict text comprehension during connected text reading

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Abstract

The present study investigates the relation between the reading process and text comprehension during naturalistic text reading. To that end, participants read easy and difficult texts while their eye movements were recorded. After each reading, participants filled-in comprehension questionnaires. We investigated classical measures of the reading process related to comprehension (fixation duration, regressive eye movements), as well as power-law scaling in eye movements that are indicative of degree of cognitive coordination during reading. The results show that text difficulty led to longer fixation durations and stronger power-law scaling in eye movements. Moreover, the degree of power-law scaling in eye movements was predictive of text comprehension. In line with previous research on natural text reading that utilized the self-paced reading method, power-law scaling turned out to be a superior predictor of reading comprehension compared to standard measures, suggesting that it is an effective measure of cognitive performance in complex reading tasks.

Keywords: naturalistic text reading; connected text reading; comprehension; power-law scaling; eye movements.

Comprehension And The Temporal Coordination Of The Reading Process

The perceptual process of reading (reflected in reaction times or eye movements, for example) and the cognitive outcomes of reading (i.e., text comprehension) have largely been studied separately. While most research on the reading process has been concerned with the (perceptual) front-end of the reading process, research on text comprehension has worked on 'back-end' problems, such as how readers remember texts or draw inferences based on textual information (Carpenter, Miyake, & Just, 1995). However, these 'back-end' studies usually do not incorporate 'front-end' process measures of reading. Most models of reading seem to assume that the 'early' processes in reading (e.g., perceptual and lexical access processes) are fairly independent of 'later' comprehension processes (McNamara & Magliano, 2009 – but see Gough & Tunmer, 1986).

Indeed, relating process aspects of reading to text comprehension has proven difficult: Research collecting measures of process and comprehension on readings of the same text is rare. The few studies that exist either do not report relations between process and comprehension measures (e.g., Zwaan, Magliano, & Graesser, 1995) or report null-effects between classical process measures – such as reading speed – and text comprehension (e.g., LeVasseur, Marcuso, & Shankweiler, 2008).

One of the problems is that the popular single word or single sentence reading research paradigms are not readily applicable to reading of naturalistic, connected texts: For example, the effects of lexical variables play only a marginal role in the process of text reading that is highly non-stationary over the course of reading (Wallot, Hollis, & van Rooij, 2013). Similarly, situation model variables that affect comprehension in short snippets of texts do not exhibit the same effects in reading of long, connected texts (McNerney, Goodwin, & Radvansky, 2011).

An alternative model proposes that the process of text reading is inherently different from situations where readers face unconnected snippets of text. During more complex cognitive tasks, idiosyncrasies (i.e., individual background knowledge, learning histories, strategy use, etc.) start to matter more, and even basic cognitive skills can assume different roles, and compensate for one another (Rasinski, 2000). Hence, a complex cognitive task such as text reading might be better understood as a coordinative problem, that is, how reader idiosyncrasies and cognitive components coordinate with each other to yield an observed level of performance (Wallot & Van Orden, 2011).

For the case of reading in particular, a well functioning reading process is a smoothly running process in which only few, small perturbations (e.g., extraordinary long reading times, regressive eye movements, periods of increased volatility reading times etc.) occur and where the text generally exerts a regulating structure on reading behavior (Wallot, 2014), such as measures of reaction times or of eye movements. In particular, measures of power-law scaling in reading times that quantify the regularity of the reading process have recently been shown to make for superior predictors of text comprehension compared to standard measures such as reading speed (Wallot, O'Brien, Haussmann, Kloos, & Lyby, 2014). However, these findings were obtained in self-paced reading tasks in which readers press a response key to reveal each new word. Self-paced reading tasks show in general similar results compared to eye movements during reading (Rayner & Pollatsek, 1994). However, we seek now to expand the findings of Wallot et al. (2014) to a more generic framework by investigating eye movements during reading. Whereas Wallot et al. (2014) used times between key presses in self-paced reading, we used eye-tracking data for measures of the reading process.

In the following sections, we will give a brief introduction of power-law scaling in the context of eye movements, then describe the rationale of the study and the selection of the dependent variables, and finally present results on the relation between the reading process (as viewed through eye movement measures) and reading comprehension.

Scaling in eye movements

The present work will deal with estimating power-law scaling from time-series of eye tracking data. Power-law scaling denotes a power-law relation between the size of changes in the measured variable and the frequency with which changes of that size occur.

For the present research, we estimate scaling by detrended fluctuation analysis (DFA - Peng, Havlin, Stanley & Goldberger, 1995). DFA quantifies how variance of a time series changes with time scale. It segments a time series using nonoverlapping windows whose length indicates time scale, and estimates the average variance per window length. If the logarithm of the variance changes approximately linearly with the logarithm of window size, then the slope of this linear change estimates the Hurst exponent (H) defining the power-law scaling relationship. Figure 1 illustrates the analysis on a time series of reading times.

If $H \approx 0.5$, then the data points in the time series are relatively independent of each other, conforming to white noise and indicating the absence of temporal coordination in the reading process. If $H \neq 0.5$, then this indicates that the time series exhibits power-law scaling properties that are indicative of interdependence of data points across many scales and reflective of the coordination of cognitive processes during a task (Van Orden, Holden, Turvey, 2003). Scaling manifests in behavioral (Coey, Wallot, Richardson, & Van Orden, 2012) and neurophysiological (Lowen, Ozaki, Kaplan, Saleh, & Teich, 2001) measures of eye movements. Variations of H in behavioral and neurophysiological measures indicate situational or habitual differences in cognitive coordination that are, for example, predictive of different kinds of occulomotor control processes (Shelhamer, & Joiner, 2003), or the ability of speeded visual search (Stephen & Anastas, 2011).

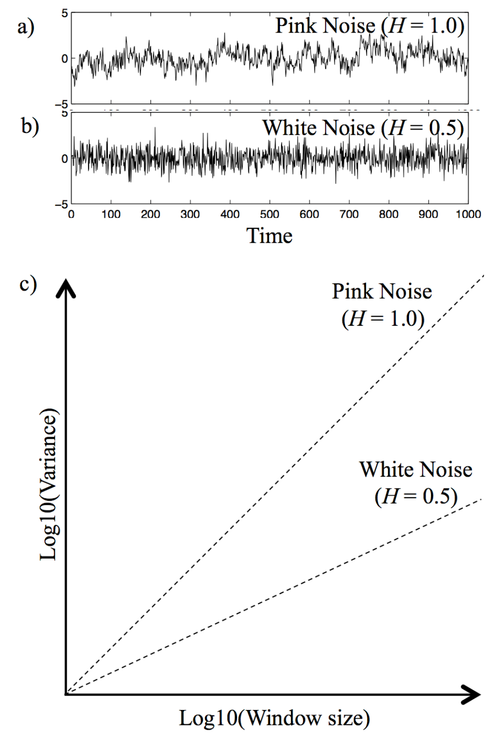

Figure 1. Illustration of scaling relationships for time series with different power-law scaling exponents. The upper time series (pink noise, Figure 1a) exhibits a scaling exponent of H = 1.0, indicating power-law scaling and interdependence of values in the time series. The lower time series (white noise, Figure 1b) exhibits a scaling exponent of H = 0.5, indicating that the values of the time series are fairly independent. Figure 1c shows the associated scaling plots.

Power-law scaling has been observed not only in eye movement components, such as fixations (Aks, Zelinsky, & Sprott, 2002) and saccades (Shelhamer, & Joiner, 2003), but also in the fluctuations of the raw eye movement record, the gaze step size (Stephen & Mirman, 2010), which incorporates both, fixational and saccadic eye movements. Figure 2 illustrates the computation of fixations and gaze step size from a horizontal snippet of gaze positions measured by an eye tracker during reading, exhibiting the famous staircase of eye movements during reading (Figure 2a). Usually, fixations are extracted by applying a criterion that dissects the different steps into their vertical and horizontal components: saccades and fixations, respectively (Figure 2b). In contrast, to calculate the gaze step size of the eye movement record, the positions of the record are differenced (Figure 2c).

Fixations are the main components of eye movements thought to reflect cognitive processing (Rayner, 1998). Hence, we would expect scaling in fixations time series during reading to be informative about cognitive coordination related to reading comprehension. On the other hand, gaze steps have been shown to capture scaling properties of eye movements across fixations and fluctuations (Kelty-Stephen & Mirman, 2013; Stephen & Mirman, 2010; Wallot, Coey, & Richardson, 2015), and hence might capture a coordination of cognitive processes pervading throughout the components of eye movement behavior (Wallot & Kelty-Stephen, 2014). Hence, the present research will investigate scaling both at the level of fixations and at the level of gaze steps.

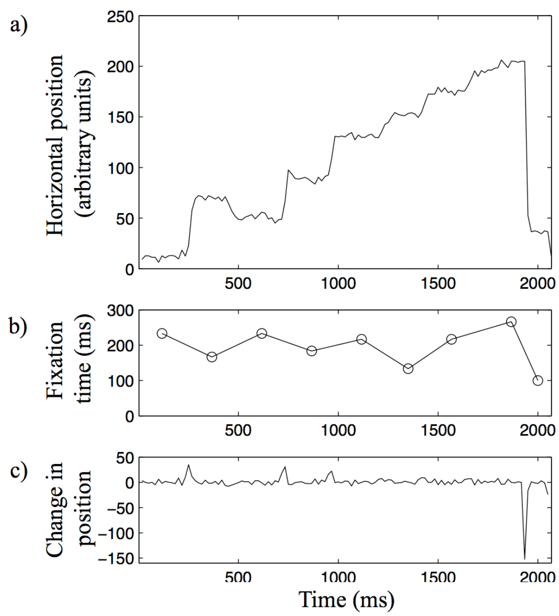

Figure 2. Illustration of the calculation of fixation and gaze step size time series based on the raw eye movement record of positions. The horizontal gaze positions exhibit the staircase patters during reading (Figure 2a). In order to extract fixations, the steps are isolated according to some criterion and summed into fixation durations (Figure 2b). In contrast, the gaze step size is simple the differenced record of positions (Figure 2c).

The Reading Study

As noted above, standard metrics of the reading process, such as reading speed, have been unsuccessful at predicting reading comprehension (e.g., LeVasseur et al., 2008). However, eye movements allow a more fine-grained description of the reading process, such as the quantification of regressive eye movements. To investigate the role of scaling in eye movement with regard to reading comprehension at the level of fixational eye movements, we reanalyzed the data from Wallot (2011) where participants read an easy and a difficult text while their eye movements were being recorded, and then filled-in comprehension questionnaires after each reading.

To investigate the role of scaling properties of eye movements as predictors for the reading process, we calculated scaling exponents for fixations and for gaze step size (see Wallot & Kelty-Stephen, 2014). We also calculated eye-movement measures shown to reflect comprehension processes in reading (i.e., fixation duration, number of fixations, number of regressive eye movements – see Rayner, Chace, Slattery & Ashby, 2006). We sought to test whether eye movement components that have been associated with comprehension processes in such studies will transfer to connected text. In particular, we predicted that better comprehension should follow from reading with briefer fixation durations and faster overall reading times, fewer fixations, and fewer regressive eye movements (Rayner et al., 2006).

Moreover, we sought the same effects in eye-movement measures that Wallot et al. (2014) had found in reading times during self-paced reading. That is, we predicted that better comprehension should follow from reading with greater independence amongst eye movements. We assessed power-law scaling in both, fixation durations and gaze-step series, the latter measure capturing coordination of the reading process that pervades its different components, such as fixations and saccades (Wallot & Kelty-Stephen, 2014).

Method

Participants

Overall, n = 32 students participated in the study. Part of the sample (n = 24 participants) came from research that was part of a dissertation (Wallot, 2011). Twenty-eight were students of the University of Cincinnati, 4 were non-students (average age: 27.52 years, ranging from 20 to 47 years). Twelve (37.5%) were female. All were native speakers of English and all had normal or corrected-to-normal vision. All participants read the easy and difficult texts on two separate occasions. Half (n = 16) read the text by pressing a response key to reveal each new sentence in a self-paced manner, the other half read the text screen-by-screen.[1] Participants' eye movements were recorded during both conditions.

The eye movement recordings of four participants had to be dropped from the analysis, because the records were highly erratic or the eye tracker had lost the corneal reflection too often during recording.

Apparatus And Stimuli

The texts used were the first five chapters of 'The House Of The Scorpion' by Nancy Farmer and the first two chapters of 'Infinite Jest' by David Foster Wallace. Both stories were fictional dystopias, hence belonging to the same genre. Furthermore, fictional stories were picked because this prevented readers form utilizing specific world knowledge during the reading of the text. Both texts had approximately the same length, but differed in aspects of text difficulty (see Table 1).

[1] Preliminary analyses did not reveal significant effects of presentation mode. Hence, this factor was not further pursued.

The texts were presented in Courier New font (14 pt.) on a standard 13-inch computer monitor (1280 x 1024 px.). The program that controlled stimulus presentation was a MatLab© PsychophysicsToolbox (Brainard, 1997). Participants' eye movements were recorded by an Applied Science Laboratory D6© remote eye-tracking system with a temporal resolution of 60Hz and a maximal spatial resolution of 0.5° visual angle.

Table 1. Text characteristics.

Text Characteristic	House of the Scorpion	Infinite Jest
Number of Words	12,902	12,390
Sentence Length	*M* = 9.6 (*SD* = 5.3)	*M* = 20.7 (*SD* = 20.2)
FK Readability index	3.7	9.3

Procedure

To read each story, participants came to the laboratory two times on two different days (presentation order was counterbalanced across participants). During reading, participants sat in front of the computer monitor, app. 79 cm away from the screen. Experimenters instructed participants that the text would be displayed either sentence-by-sentence or screen-by-screen (this mode remained constant within each participant, so that each participant read both stories in the same way), and that the eye-tracker would record their eye movements during reading.

Experimenters asked participants to read the text at their natural reading speed. After participants finished reading, experimenters asked participants to rate text difficulty, write a brief summary[2], and to complete a comprehension questionnaire of which they had been forewarned. Each questionnaire consisted of 36 statements about the text that participants had to judge as being right or wrong.

Data Analysis

A total of 4.7% of the data were lost due to the eye tracker loosing the eyes during reading or participants looking away from the screen.

An acceleration-based criterion extracted fixations during reading (Araujo, Kowler, & Pavel, 2001): Increases in acceleration of the eye-movement record indicated the onset of a saccade, while decreases in acceleration indicated the end of a saccade and the onset of a fixation. The algorithm that implemented the acceleration-criterion based separation procedure was taken from Hidalgo-Sotelo (i.e., Rich, Kunar, Van Wert, Hidalgo-Sotelo, Horowitz, & Wolfe, 2008) and operated in the following way: The time-series of eye-movement positions was divided into overlapping windows of adjacent data points with a window size of 4 (equaling 68 ms) and a step-size of 1. The acceleration threshold that marked the onset of a saccade was set to a change in velocity of 2° of visual angle per second between two consecutive intervals (Abrams, Meyer, & Kornblum, 1989). Gaze step-size was calculated as the difference of positions in the eye movement record (Stephen & Mirman, 2010).

Scaling exponents in eye movements on the levels of fixations, and gaze step size was determined using DFA (Peng, et al., 1995) with a minimum bin size of 4 and a maximum bin size of ¼ of the length of the respective time-series (see also 'Scaling In Eye Movements'). While the scaling functions of fixations where linear, the scaling functions of gaze steps revealed two distinct scaling regions, a steep one on faster time scales (between 15ms and 21sec) and a more shallow one on slower time scales (between 30sec and 10min) (see Figure 3). Hence, scaling exponents were calculated separately for fast and slow time scales in gaze steps series, yielding two values for scaling in gaze step size per participant.

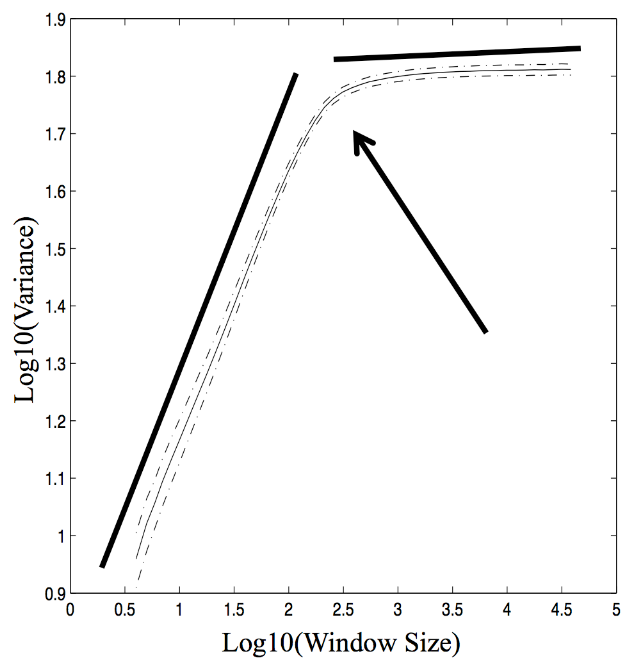

Figure 3. Scaling function of gaze steps and associated standard error. The scaling function exhibits two distinct scaling regions on fast and slow time scales (black lines) that are divided by an inflection point (black arrow).

Repeated measures *t* statistics tested for effects of text difficulty on the resulting measures. Multiple regression tested the effect of different eye movement characteristics as predictors of the outcome measure of comprehension scores.

Results

Effects of Text Difficulty

Comprehension scores (i.e., the number of correct answers on the multiple-choice comprehension questionnaire) were higher for the easy text compared to the difficult text (M_{easy}

[2] Analysis of the summaries has not yet been conducted. Hence, the are not currently incorporated into the comprehension measure.

= 28.35, M_{diff} = 26.34; $t(27)$ = 3.50, p = .002) and overall reading duration was shorter for the easy text compared to the difficult text (M_{easy} = 48.07min, M_{diff} = 52.70min; $t(27)$ = -3.93, p = .001).

Compared to easy text, difficult text elicited longer fixation durations (M_{easy} = 202ms, M_{diff} = 220ms; $t(27)$ = -3.34, p = .003), a marginally higher number of fixations (M_{easy} = 6439, M_{diff} = 6840; $t(27)$ = -1.95, p = .063), but did not result in an increased number of regressive eye movements ($t(27)$ = 0.19, p = .850).

Furthermore, scaling in fixations increased significantly from easy text reading to difficult text reading (M_{easy} = 0.55, M_{diff} = 0.58; $t(27)$ = -2.86, p = .008). Similarly, scaling in gaze step-size on slower time-scales increased significantly from easy text reading to difficult text reading (M_{easy} = 0.01, M_{diff} = 0.02; $t(27)$ = 2.38, p = .025), but no effect was observed in scaling on faster time scales ($t(27)$ = 0.85, p = 423). Obviously, both scaling in fixations and scaling in gaze step-size are sensitive to the reading of different text difficulty levels.

Prediction of Reading Comprehension

All predictors were simultaneously entered into the regression model, which accounted for 31.0% (adjusted R^2 = .207; $F(7, 47)$ = 3.01, p = .011) of the variance in comprehension scores. Inspection of variance inflation suggested that multicollinearity between predictors was not problematic (all VIF < 5; O'Brien, 2007).

Only the scaling exponents of fixations and scaling exponents of the gaze steps on slower time scales turned out to yield significant unique predictive power of comprehension scores (see Table 2).

Table 2. Regression of comprehension scores onto properties of eye movements during reading.

Predictor	β	t	p
Intercept		6.63	< .001
Fixation Duration	.204	0.66	= .513
No. of Fixations	-.222	-0.37	= .583
Regressions	-.182	-1.18	= .243
Overall Duration	.177	0.27	= .792
Scaling Fixations	-.289	-2.11	= .041
Scaling Gaze Steps (Fast)	.221	1.36	= .181
Scaling Gaze Steps (Slow)	-.359	-2.58	= .013

Discussion

The present findings on eye movements during natural text reading extend and corroborate previous research that used self-paced reading. First, they add to recent findings that investigate the role of reading process components in natural text reading and find that many of the aspects of reading that seem to be important in reading of single words, sentences, or short snippets of texts do not transfer to reading of natural, connected texts (McNerney et al., 2011; Wallot et al., 2013). In particular, the effects of text difficulty on number of fixations and regressive eye movements are greatly reduced when long, natural texts are read compared to shorter texts (cf. Rayner et al., 2006).

Second, the present results extend findings on the relation between reading process and comprehension: Again, when natural texts are used, standard measures such as fixation duration, number of eye movements, regressive eye movements and overall reading speed do not substantially predict reading comprehension (cf. Levasseur et al., 2008).

Both of these findings suggest that complex reading tasks work differently from simple reading tasks. As has been argued elsewhere (Wallot et al., 2014), the difference between simple and complex reading tasks might lie in the coordination of cognitive processes during reading, and that one needs to find adequate measures of this coordination in order to address questions such as how the reading process in complex reading tasks reflects text comprehension. Instead of asking how specific aspects of a text lead to specific effects in reading behavior, one can ask a broader question, which is to what extent does the text effect and structure reading behavior (Wallot, 2014). One measure that can address such questions is the degree of power-law scaling (Van Orden et al., 2003) that can be observed in time series of reading behavior, such as eye movements: Power-law scaling in eye movements during reading imply that the processes that drive eye movements during text reading are not just a result of the local information presented by the foveally fixated word, parafoveal and short-term semantic priming, but are coordinated across multiple time scales potentially spanning the whole text that has been read up to that point.

Previous research on self-paced reading found that better comprehension goes along with weaker power-law structure in reading times (Wallot et al., 2014). Our results extend those findings by showing that weaker power-law structure in eye movements was also associated with better comprehension. Even though the theoretical significance of power-laws in reading is still not clear, shallower power-law structure close to white noise might indicate a more highly constrained reading process, which is driven primarily by properties of the text and not by voluntary eye movements (Kloos & Van Orden, 2010), which in turn seems to be an indicator of high levels of reading skill (Wallot et al., 2014). Moreover, changes in power-law scaling that relate to reading comprehension resided mostly on slower time scales, which fits with current theories of online comprehension during reading that assume comprehension processes to be slower than individual instances of word reading, for example (Donald, 2007). However, the fact that comprehension was reflected in eye movements by virtue of scaling properties suggests that comprehension might not be so much brought about by *distinct* cognitive components, but by the coordination processes of the cognitive system that integrate information across multiple time scales.

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