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Reading Comprehension as Embodied Action: Exploratory Findings on Nonlinear Eye Movement Dynamics and Comprehension of Scientific Texts

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Abstract

Reading comprehension is often conceptualized in terms of the internal processing of linguistic information and construction of accurate mental representations. In contrast, an ecological-enactive approach rejects this internalist focus and instead emphasizes the dynamic process of reader-text coupling in which eye movements play a constitutive role. In this study, we employed recurrence quantification analysis (RQA) to examine the relationship between reading comprehension and eye movement dynamics, based on eye-tracking data from the Potsdam Textbook Corpus recorded from beginners and experts reading scientific texts, followed by comprehension questionnaires. Moreover, we compared the findings from RQA to classical eye movement measures (number of fixations, mean fixation duration, regression fixation proportion). The results indicated that classical eye movement measures did not predict reading comprehension reliably, whereas recurrences in gaze steps were reliably associated with reading comprehension proficiency. Contrary to our original hypothesis, experts showed more irregular, rather than more regular, eye movement dynamics, and these were linked to more proficient reading comprehension. In line with previous research on naturalistic reading using nonlinear methods, the present findings suggest that reading comprehension is best understood as emerging from interaction-dominant coordination processes.

Keywords: reading comprehension; eye movements; naturalistic reading; recurrence quantification analysis; ecological psychology; enactivism.

Introduction

Ecological psychology (J. J. Gibson, 1979) and enactivism (Di Paolo & Thompson, 2014; Varela, Thompson, & Rosch, 1991/2017) have provided promising frameworks to re-conceive cognition in non-representational and non-computational terms. Despite recent efforts to establish wider acceptance of the view that cognition is fundamentally grounded in situated interaction of embodied agents (Dingemanse et al., 2023), a prevalent critique articulated by proponents of computationalism is that ecological-enactive approaches fail at explaining so-called "representation-hungry" higher-order cognitive abilities such as language, imagination, memory, or abstract problem solving, without invoking mental representations (Adams & Aizawa, 2019; Clark & Toribio, 1994; Edelman, 2003). Although several replies to this critique have already been formulated on the basis of theoretical arguments (Degenaar & Myin, 2014; Sanches de Oliveira, Raja, & Chemero, 2021; Zahnoun, 2021), the ultimate test of these theories depends on the success of a research program that takes seriously the implications of ecological-enactive cognitive science in its day-to-day research (Chemero, 2009).[1]

Here, we aim to advance an ecological-enactive conception of reading comprehension empirically—reading comprehension being a prime example of "real cognition".

Echoing the representationalist stance, contemporary psycholinguistic theories of reading comprehension are still based on the situation model (van Dijk & Kintsch, 1983), which posits that successful reading comprehension requires a mental representation of information contained in the text, enriched by inferences and prior knowledge (for review, see Ferstl, 2018). According to this view, the eyes feed visual stimulation to the brain, and comprehension is detached from the written words and syllables; it only happens in the brain after sufficient post-processing of the visual input.

In contrast, an ecological-enactive account of reading comprehension emphasizes the involvement of the whole body, in addition to the brain, and rejects representations as the key to comprehension (Trasmundi, Toro, & Mangen, 2022; van den Herik, 2019; van Elk, Slors, & Bekkering, 2010). On this view, reading comprehension emerges from direct reader-text coupling; it does not necessitate representation as a mediator between the text and the reader. In terms of the Gibsonian notion of affordances, a text affords both reading and comprehending. As affordances break up the dichotomy between internal and external, subjective and objective (Chemero, 2009; J. J. Gibson, 1979), so does reading comprehension emerge dynamically from brain-body-text interaction. Comprehension in itself is not seen as an outcome but an integral part of the reading process. In order to comprehend, the reader needs to actively engage with the text to discriminate ecological information[2]: "Literacy does not consist of being able to give a name or a sound upon presentation of a written character. Neither is it passive acquisition of an image somewhere in the head that a written word can then be matched to. Reading is an active process, self-directed by the reader in many ways and for many purposes." (E. J. Gibson & Levin, 1975, p. 5).

[1] In using the label "ecological-enactive cognitive science", we identify with recent efforts to develop a unified theoretical framework for radical embodied cognitive science that builds on ecological psychology and enactivism as complementary theories (Baggs & Chemero, 2021).

[2] See Thomas, Riley, and Wagman (2020) for a discussion of ecological information, in contrast to the notion of information presupposed by computationalism.

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It follows from an ecological-enactive conception of reading comprehension that eye movement dynamics should be informative of readers' comprehension proficiency. Although studying eye movements in the context of reading comprehension has a long tradition in psycholinguistics, eye movements are typically regarded as providing insight into the internal processing of linguistic information and top-down oculomotor control (Staub & Rayner, 2007). In contrast, an ecological-enactive account holds that eye movements play a *constitutive* role in reader-text coupling, and thus eye movement dynamics should provide an indicator of reading comprehension as they reflect modes of reader-text coupling.

Surprisingly few studies have explicitly investigated the relationship between eye movements as a process measure and reading comprehension of connected texts under naturalistic conditions, and these studies have not provided conclusive evidence. While some studies looking at connected text reading found that shorter mean fixation duration and less regressive eye movements correlated with more proficient reading comprehension (Rayner, Chace, Slattery, & Ashby, 2006; Southwell, Gregg, Bixler, & D'Mello, 2020; Kim, Petscher, & Vorstius, 2019; Copeland & Gedeon, 2013), other studies reported contradictory findings (D'Mello, Southwell, & Gregg, 2020) or did not find any relationship between reading comprehension and classical eye movement measures (Wallot, O'Brien, Coey, & Kelty-Stephen, 2015).

One of the reasons why there has been no conclusive evidence thus far may be that most of the studies looking at eye movements and reading comprehension were based on linear aggregate measures which presuppose component-dominant causation, i.e., unidirectional causality from underlying mechanisms to observed outcomes. In contrast, the concept of reader-text coupling entails non-decomposable dynamical feedback loops, making the focus on interaction-dominant causation more adequate from an ecological-enactive stance (Blau & Wagman, 2023; Moreno, Ruiz-Mirazo, & Barandiaran, 2011; Wallot & Kelty-Stephen, 2018).

Since nonlinear methods provide the mathematical tools to model interaction-dominant causation, we use recurrence quantification analysis (RQA) in the present study to investigate the relationship between eye movement dynamics and reading comprehension proficiency among beginners and experts reading scientific texts. Based on the concept of *reading time regularity* (RTR) that allows to capture reader-text coupling (Tschense & Wallot, 2022), we expect more regular eye movement dynamics, reflected in increased RTR, to be indicative of more skillful reader-text coupling and thus increased reading comprehension proficiency. Moreover, we compare the findings from RTR against classical eye movement measures, and we hypothesize that the latter do not predict reading comprehension reliably.

Method

The present study was based on publicly available data from the Potsdam Textbook Corpus (Jäger, Kern, & Haller, 2021).

Participants

75 participants (36 male, 39 female; mean age 24) were recruited and tested by Lena A. Jäger at the University of Potsdam, Germany, between 2015 and 2017 (Jäger et al., 2021). All participants were at least 18 years old, neurologically healthy, had normal or corrected to normal vision, and were fluent in written and spoken German. Moreover, all participants were either pursuing an undergraduate degree in biology or physics, or they had already graduated at the time of testing. Participants who had already graduated in biology or physics were considered experts ($n_{bio} = 27$; $n_{phy} = 20$), whereas undergraduate students were categorized as beginners ($n_{bio} = 16$; $n_{phy} = 12$).

Materials

12 scientific texts were taken from German undergraduate-level textbooks; six texts from biology and six texts from physics textbooks. Each text was approximately 160 words in length and provided a concise technical description of a phenomenon or an experimental technique specific to either biology or physics.

For each text, there were two sets of three single-choice questions with four answer options each, one on (i) text comprehension and the other on (ii) background knowledge. Comprehension questions could be answered correctly solely based on the information contained in the text; background questions referred to the same topic but required additional knowledge, not provided in the text, to be answered correctly.

Eye movements during reading were recorded using an EyeLink 1000 Plus eye-tracker (SR-Research, Ottawa, Ontario, Canada) for monocular recording of the right eye at a sampling rate of 1000 Hz. Eye-to-screen (61 cm) and eye-to-camera distance (65 cm) were constant across participants.

Procedure

In each trial, participants read one of the texts followed immediately by comprehension and background questions. Every text was presented at once on a 22-inch monitor (1680 x 1050 pixels) in monospaced white font (Courier, font size 18) on black background, and there was no time limit regarding the total reading duration. Every participant read both biology and physics texts, regardless of their academic background, thus resulting in 12 trials per participant. The order of texts and answer options was randomized across participants.

Data Analysis

All analyses were conducted in R 4.2.1 (R Core Team, 2022) using RStudio 2022.07.0 (RStudio Team, 2022).

For both comprehension proficiency and background knowledge, we calculated accuracy scores ranging from $[0,1]$, based on the fraction of correctly answered questions.

In the published data by Jäger et al. (2021), fixations had already been extracted automatically using the EyeLink Data Viewer software (SR-Research, Ottawa, Ontario, Canada) and subsequently corrected manually for calibration error. Based on the preprocessed fixation data, we calculated three commonly used indicators of eye movements: (i) total number of fixations, (ii) mean fixation duration, and (iii) fraction of regressive eye movements.

Recurrence Quantification Analysis (RQA) RQA is a nonlinear method inspired by dynamical systems theory that essentially captures autocorrelation in time series data (Webber & Zbilut, 1994). The general idea is that, given a time series of a single observable, one can recover the dynamics of an interdependent higher dimensional system, and recurrences will be informative of coordination properties of that system over time. RQA provides various outcome measures (Marwan, Romano, Thiel, & Kurths, 2007), and in the present study, we focused on recurrence rate (RR), determinism (DET), average diagonal line length (ADL), maximum diagonal line length (MDL), and laminarity (LAM). RR is an indicator of the total amount of recurrence and thus repetitiveness within a system, while the remaining measures quantify the temporal structure of recurrences. DET, ADL, and MDL are informative about repeated connected trajectories, i.e., the system is undergoing change, but in a highly deterministic way. In contrast, LAM reflects repetitions of the same state of the system over a period of time, similar to an attractor point. For a comprehensive tutorial, see Wallot (2017).

Reading Time Regularity (RTR) As for operationalizing RTR, we applied RQA to raw gaze instead of fixation data and replicated the analysis procedure described by Tschense and Wallot (2022). Eye blinks were detected and removed based on pupillometry noise (Hershman, Henik, & Cohen, 2018). If more than 10% of the data points of a trial were affected by eye-blinks, we excluded that trial from subsequent analysis. Based on the cleaned gaze data, we calculated a one-dimensional gaze step time-series by taking the euclidean distances between all consecutive gaze positions. Before subjecting the gaze step time-series to RQA, we applied z-transformation and removed extreme values $+/-10SD$. We used the *crqa* package in R (Coco, Mønster, Leonardi, Dale, & Wallot, 2021) to run RQA with a delay parameter of $\tau = 15$, an embedding dimension of $D = 5$, and a radius of $r = 0.2$ ($M_{RR} = 8.4\%$; $SD_{RR} = 8.09$). Due to computational limits, we performed piecewise RQA for each trial with several overlapping time-windows of 10,000 data points, a step size of 5,000 data points, and took the average across all piecewise RQA measures to obtain the final RQA outcome measures.

Inferential Statistics Out of 900 trials, 839 trials remained for the statistical analysis; 61 trials were excluded due to missing behavioral data or excessive eye-blinks. Since all participants read both biology and physics text, we differentiated between congruent and incongruent contexts, depending on whether the text type (biology or physics) was (in)congruent to participants' major (biology or physics). The reasoning here was that an effect of expertise that is specific to expertise in either biology or physics should manifest in a significant difference in comprehension proficiency and eye movement characteristics between beginners and experts in the congruent context, whereas there should be no significant effect in the incongruent context. We conducted pairwise tests for each of the four subgroups (beginners vs. experts | congruency x major) using unpaired non-parametric Wilcoxon-Mann-Whitney rank sum tests, because the data did not meet the assumptions of a non-parametric ANOVA on ranks. Moreover, we corrected for multiple comparisons using Bonferroni correction, given a family size of $n = 4$ (congruency x major). All p-values were adjusted accordingly.

Results

Behavioral Data

As expected, only in the congruent context, experts showed significantly more background knowledge than beginners in both the biology ($M_{beg} = .449$; $SD_{beg} = .33$; $M_{exp} = .622$; $SD_{exp} = .301$; $W = 8128.5$; $^{***}p_{adj} = .0003$; $r = .259$) and the physics group ($M_{beg} = .285$; $SD_{beg} = .251$; $M_{exp} = .405$; $SD_{exp} = .303$; $W = 4907$; $^{*}p_{adj} = .0186$; $r = .191$). In contrast, in the incongruent context, beginners and experts did not differ significantly in background knowledge in both the biology ($M_{beg} = .28$; $SD_{beg} = .254$; $M_{exp} = .255$; $SD_{exp} = .25$; $W = 6089.5$; $p_{adj} = 1$; $r = .049$) and the physics group ($M_{beg} = .426$; $SD_{beg} = .309$; $M_{exp} = .383$; $SD_{exp} = .308$; $W = 3785.5$; $p_{adj} = 1$; $r = .063$).

As for comprehension proficiency, biology experts showed

Table 1: Group differences between beginners and experts in biology in congruent and incongruent contexts. $^{+}p_{adj} < .1$, $^{*}p_{adj} < .05$, $^{**}p_{adj} < .01$.

	MD_{beg}	SD_{beg}	MD_{exp}	SD_{exp}
Congruent Context				
Classical Eye Movement Measures				
Fix. total*	423	210.06	363	152.16
Fix. dur. (msec)*	209.74	14.16	220.26	20.59
Regressions (%)	21.78	6.27	24.7	8.04
Reading Time Regularity				
RR (%)$^{+}$	10.76	8.8	6.32	8.77
DET (%)*	82.11	31.37	65.71	30.13
ADL (px)$^{+}$	3.88	7.46	2.92	8.65
MDL (px)$^{+}$	155	305.58	69.77	673.1
LAM (%)*	88.99	26.84	78.61	25.06
Incongruent Context				
Classical Eye Movement Measures				
Fix. total	465	228.99	426.5	177.35
Fix. dur. (msec)**	214.86	12.13	224.4	21.82
Regressions (%)	21.58	6.35	25.05	7.91
Reading Time Regularity				
RR (%)	9.32	8.51	6.19	8.61
DET (%)	77.71	32.31	64.28	30.74
ADL (px)	3.45	6.8	2.87	8.58
MDL (px)	109.29	238.94	63.52	612.53
LAM (%)	86.3	27.72	78.02	26.12

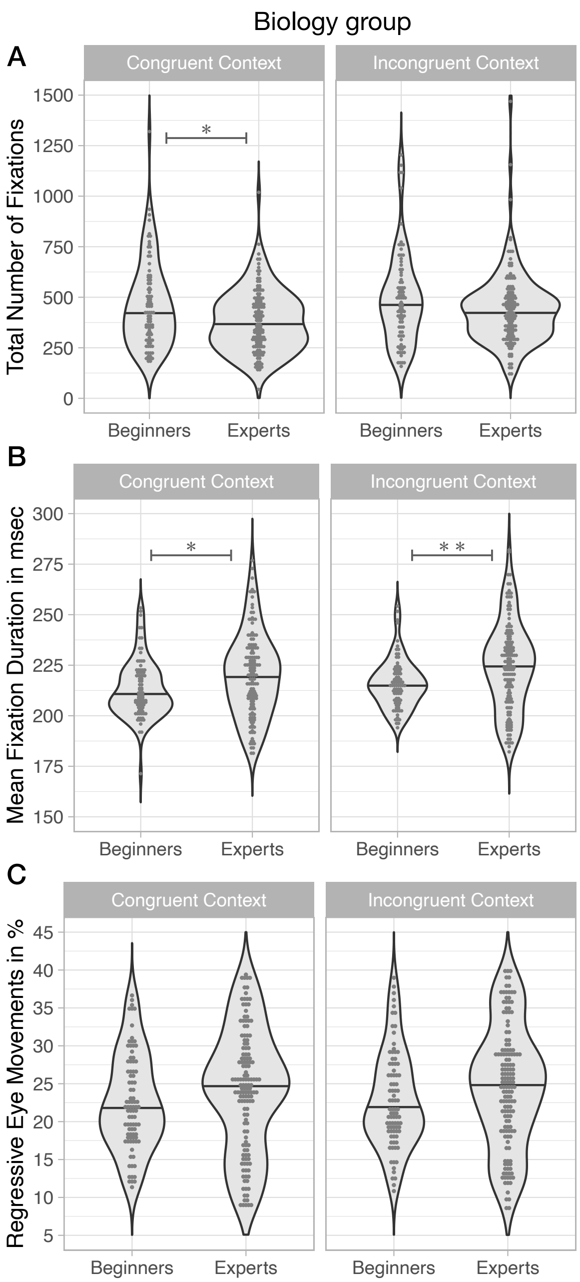


Figure 1: Group differences between beginners and experts in biology in (A) total number of fixations, (B) mean fixation duration, and (C) regressive eye movements. $^{*}p_{adj} < .05$, $^{**}p_{adj} < .01$.

significantly better comprehension proficiency than biology beginners in the congruent context ($M_{beg} = .73$; $SD_{beg} = .251$; $M_{exp} = .825$; $SD_{exp} = .247$; $W = 7652$; $^{**}p_{adj} = .0078$; $r = .204$). Surprisingly, in the congruent context, there was no significant difference in comprehension proficiency between physics experts and beginners, although the data indicated a numeric trend towards better comprehension proficiency among physics experts ($M_{beg} = .604$; $SD_{beg} = .304$; $M_{exp} = .689$; $SD_{exp} = .272$; $W = 4643$; $p_{adj} = .2803$; $r = .133$). As expected, in the incongruent context, there were no significant differences in comprehension proficiency between experts and beginners both in the biology ($M_{beg} = .533$; $SD_{beg} = .294$; $M_{exp} = .509$; $SD_{exp} = .312$; $W = 6251$; $p_{adj} = 1$; $r = .026$) and the physics group ($M_{beg} = .633$; $SD_{beg} = .311$; $M_{exp} = .617$; $SD_{exp} = .337$; $W = 4014.5$; $p_{adj} = 1$; $r = .014$).

Classical Eye Movement Measures

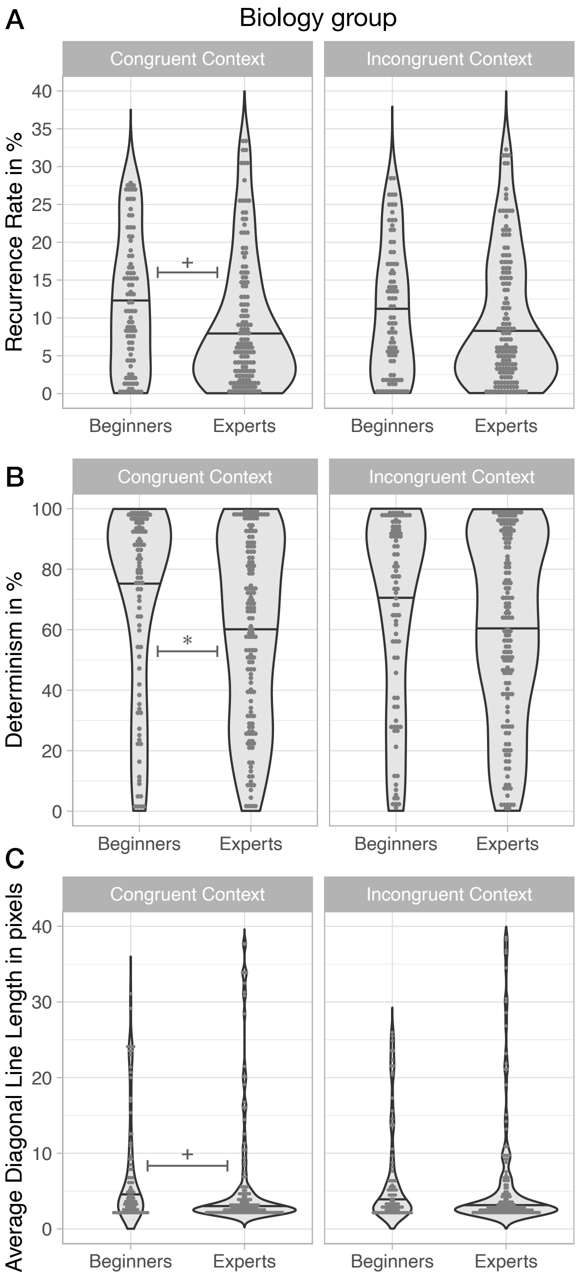
In the congruent context, biology experts exhibited significantly less fixations in total ($W = 5022.5$; $^{*}p_{adj} = .0436$; $r = .168$) and significantly longer mean fixation duration ($W = 7623.5$; $^{*}p_{adj} = .0243$; $r = .181$) compared to biology beginners. Experts and beginners in biology did not differ significantly in the proportion of regressive eye movements in the congruent context ($W = 7189$; $p_{adj} = .2518$; $r = .123$)

Notably, in the incongruent context, biology experts also showed significantly longer mean fixation duration than biology beginners ($W = 8161.5$; $^{**}p_{adj} = .0025$; $r = .223$). Given the behavioral data, this finding raises questions about the specificity of the effect of expertise in the biology group and its association with comprehension proficiency. Moreover, there were no significant differences in total number of fixations ($W = 5634$; $p_{adj} = .4412$; $r = .104$) and proportion of regressive eye movements ($W = 7434.5$; $p_{adj} = .1912$; $r = .129$) between beginners and experts in biology in the incongruent context (see figure 1 and table 1).

In the physics group, in line with the behavioral data on

Table 2: Group differences between beginners and experts in physics in congruent and incongruent contexts.

	MD_{beg}	SD_{beg}	MD_{exp}	SD_{exp}
Congruent Context				
Classical Eye Movement Measures				
Fix. total	395	149.01	391	159.34
Fix. dur. (msec)	224.91	26.54	226.46	32.07
Regressions (%)	24.49	6.36	24.69	5.32
Reading Time Regularity				
RR (%)	3.64	8.14	3.81	4.79
DET (%)	46.46	29.73	47.68	26.78
ADL (px)	2.46	6.06	2.5	1.83
MDL (px)	29.23	425.89	34.27	145.2
LAM (%)	64.83	23.5	65.81	23.72
Incongruent context				
Classical Eye Movement Measures				
Fix. total	482	140.27	507	204.3
Fix. dur. (msec)	227.91	26.42	229.83	29.21
Regressions (%)	25.87	5.86	24.07	5.07
Reading Time Regularity				
RR (%)	5.25	8.7	3.83	5.66
DET (%)	52.24	28.45	47.36	28.61
ADL (px)	2.6	6.8	2.47	2.07
MDL (px)	33.95	546.47	28.37	134.51
LAM (%)	69.37	22.31	65.54	25.21



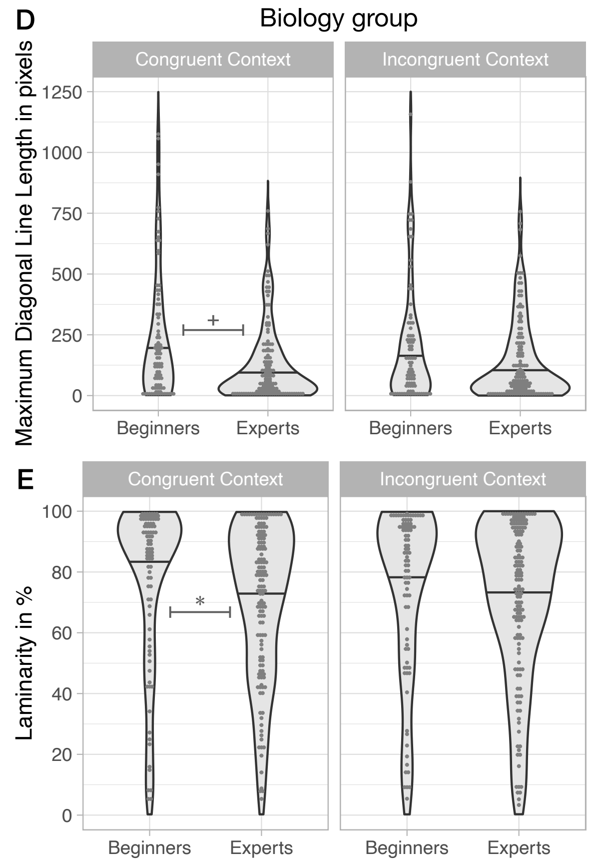


Figure 2: Group differences between beginners and experts in biology in (A) recurrence rate, (B) determinism, (C) average diagonal line length, (D) maximum diagonal line length, and (E) laminarity. $^{+}p_{adj} < .1$, $^{*}p_{adj} < .05$.

comprehension proficiency, there were no significant differences in any of the classical eye movement measures between beginners and experts, neither in the congruent context (Fix. total: $W = 4038$; $p_{adj} = 1$; $r < .001$; Fix. dur.: $W = 3965.5$; $p_{adj} = 1$; $r = .015$; Reg.: $W = 4168.5$; $p_{adj} = 1$; $r = .027$), nor in the incongruent context (Fix. total : $W = 4693.5$; $p_{adj} = .3491$; $r = .125$; Fix. dur.: $W = 4231$; $p_{adj} = 1$; $r = .031$; Reg.: $W = 3532.5$; $p_{adj} = .5084$; $r = .111$).

Reading Time Regularity

In the congruent context, contrary to what we had expected, the data revealed a negative rather than a positive modulatory effect of expertise on RTR in the biology group. Biology experts showed significantly decreased determinism and laminarity compared to biology beginners in the congruent context (DET: $W = 4996.5$; $^{*}p_{adj} = .0374$; $r = .171$; LAM: $W = 4989$; $^{*}p_{adj} = .0357$; $r = .172$), and the remaining RQA measures indicated marginally significant negative modulatory effects of expertise on RTR (RR: $W = 5131.5$; $p_{adj} = .0804$; $r = .153$; ADL: $W = 5078$; $p_{adj} = .0598$; $r = .161$; MDL: $W = 5052$; $p_{adj} = .0516$; $r = .164$).

In the incongruent context, in line with the behavioral data on comprehension proficiency, there was no significant difference in RTR between biology experts and biology beginners, as consistently reflected across all RQA measures (RR: $W = 5846$; $p_{adj} = .9592$; $r = .077$; DET: $W = 5729$; $p_{adj} = .6364$; $r = .092$; ADL: $W = 5752.5$; $p_{adj} = .6936$; $r = .089$; MDL: $W = 5788$; $p_{adj} = .7872$; $r = .084$; LAM: $W = 5722.5$; $p_{adj} = .6216$; $r = .093$; see figure 2).

In the physics group, in consistency with the behavioral findings on comprehension proficiency, there was no significant modulatory effect of expertise on RTR, as indicated by all RQA measures, neither in the congruent context (RR: $W = 3514$; $p_{adj} = .5644$; $r = .108$; DET: $W = 3542$; $p_{adj} = .6548$; $r = .102$; ADL: $W = 3517$; $p_{adj} = .5736$; $r = .107$; MDL: $W = 3590$; $p_{adj} = .8344$; $r = .092$; LAM: $W = 3542$;

$p_{adj} = .6548$; $r = .102$), nor in the incongruent context (RR: $W = 3537.5$; $p_{adj} = .5224$; $r = .11$; DET: $W = 3548.5$; $p_{adj} = .5544$; $r = .108$; ADL: $W = 3512$; $p_{adj} = .4536$; $r = .116$; MDL: $W = 3535$; $p_{adj} = .5152$; $r = .111$; LAM: $W = 3543.5$; $p_{adj} = .5396$; $r = .109$; see table 2).

Discussion

The results from the present study have demonstrated that nonlinear eye movement dynamics provided a superior predictor of reading comprehension than classical aggregate measures of eye movements. In the biology group, the behavioral data confirmed a successful manipulation of expertise in that experts showed more background knowledge and better comprehension proficiency than beginners, only in the congruent but not in the incongruent context. In line with the behavioral data on comprehension proficiency, recurrences in gaze steps reflected a significant modulatory effect of expertise among biology beginners and experts in the congruent context, but not in the incongruent context. In contrast, only mean fixation duration and total number of fixations were significantly affected by expertise in the biology group, but mean fixation duration also differed significantly between beginners and experts in biology in the incongruent context, the effect size being even larger. Hence, the data provided evidence supporting a reliable association between reading comprehension and recurrences in gaze steps in the biology group, whereas the effects of expertise on classical eye movement measures were not consistent with the behavioral data on comprehension proficiency.

As for the physics group, it is unclear why there was no significant effect of expertise on comprehension proficiency in the congruent context, despite a significant effect of expertise on background knowledge. We speculate that this might be due to the fact that participants were categorized as either beginners or experts based on their study progress, instead of using an explicit measure to assess participants' expertise, given the overall lower accuracy in background and comprehension questions in the physics group. Critically, in the physics group, both the findings from classical eye movement measures and recurrences in gaze steps were consistent with the behavioral data on comprehension proficiency in that there were no significant differences between beginners and experts, neither in the congruent nor in the incongruent context. Nevertheless, further research is necessary in order to investigate whether the association between expertise, comprehension proficiency, and recurrences in gaze steps that we found in the biology group also generalizes to other contexts.

Originally, we had expected to find a positive modulatory effect of expertise on recurrences in gaze steps: this was motivated by previous work by Tschense and Wallot (2022) showing that reading time regularity (RTR) increased as a function of increasing linguistic information, and also work by Mills, Graesser, Risko, and D'Mello (2017) who found a positive relationship between reader-text coupling and reading comprehension, albeit using linear methods to operationalize reader-text coupling. However, the present data revealed a significant association in the opposite direction, i.e., biology experts exhibited less RTR and more proficient reading comprehension than biology beginners. Although we had expected that more skillful reader-text coupling would be reflected in more regular eye movement dynamics, less regularity may be reinterpreted as more adaptivity, and greater adaptivity could also be an indicator of skillful reader-text coupling. We thus speculate that the present findings might be complementary to the work by Tschense and Wallot (2022), not only in that they extended the concept of RTR to include its association with reading comprehension, but in that reading time regularity and reading time adaptivity might be complementary constructs, depending on text difficulty and expertise. The findings of the present study were based on relatively complex technical texts, and experts were highly experienced in reading scientific texts. It thus seems plausible that proficient comprehension of complex texts requires more adaptive reader-text coupling, while proficient reading comprehension in general might require a minimal degree of regularity in reader-text coupling. However, these are new hypotheses that need to be tested rigorously by future research.

Although the findings of the present study have to be interpreted as exploratory since we did not find evidence for our original hypothesis, they support a line of research that used nonlinear methods to investigate the reading process (Wallot et al., 2015; Wallot, O'Brien, Haussmann, Kloos, & Lyby, 2014; Wijnants, Hasselman, Cox, Bosman, & Van Orden, 2012). These studies, as well as the present findings, suggest that reading comprehension emerges from dynamic coordination rather than a set of discrete linear processes. Therefore, we believe that future research on reading comprehension will profit from using nonlinear methods that are compatible with the notion of interaction-dominant causation.

A question that remains is whether it would be justified to claim that we found evidence for an ecological-enactive conception of reading comprehension, assuming that the exploratory findings of the present study had been substantiated by future research. Solely based on the data, this claim would certainly not be justified. However, if nonlinear methods are explanatorily more powerful than linear methods, as we demonstrated in the present study, it will be justified to conclude that reading comprehension can be better described as emerging from interaction-dominant than component-dominant processes. Yet, it is no longer an empirical question whether the appropriate scale to attribute interaction-dominant causation is the organism-environment system, as the ecological-enactive stance argues, or only the brain, for both positions depend on diverging philosophical preconceptions (see Sanches de Oliveira and Chemero (2015) for a discussion of this issue in an analogous context). Researchers always take some philosophical stance or other (even if only implicitly), so it is crucial to keep in mind the interrelation of empirical and philosophical matters, and the need for interdisciplinary collaboration as we move forward.

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