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PAPER

Do Highlighted Keywords and Hyperlinks Improve Reading? Evidence from Eye-Tracking

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ABSTRACT

This study investigates, via an eye-tracking experiment, the effect of visually distinguishing keywords and hyperlinks on the processes of reading and comprehending specialized text. The research sample comprised 42 undergraduate students divided into control and experimental groups (EG). The control group (CG) worked with a text without hypertext highlighting, while the EG read the same text with marked key terms and the option of hypertext navigation. Analyses of fixations, saccades, and regressions revealed that students made only minimal use of hyperlinks, and the differences between groups were not statistically significant. In both groups, attention shifted toward images at the expense of the text, and the number of regressions was higher during the first reading but decreased upon rereading after two weeks. The findings suggest that visual highlighting of keywords alone, without more comprehensive structural adjustments to the text, does not fundamentally influence reading literacy or the efficiency of comprehension.

KEYWORDS

eye-tracking, fixation, regression, educational text

1 INTRODUCTION

Research in didactics suggests that learning operates at two fundamental levels: sensory perception and rational cognition. Experimental evaluations of didactic effectiveness, together with research in pedagogy and psychology, suggest that the efficiency of perception and retention is directly proportional to the number of sensory channels activated during knowledge acquisition. By sensory properties, we generally refer to attributes that act upon one of the human senses (taste, smell, sight, touch). In the context of study materials, sight predominates.

However, the implementation of ICT in educational processes is often perceived as inefficient. From the earliest adoption of distance-learning methods, a recurring question has been whether students learning through mediated interaction receive education of comparable quality to that of students in face-to-face formats.

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Historically, the No Significant Difference Phenomenon—formulated based on at least 355 comparative studies conducted between 1928 and 1996—was widely accepted. The core claim is that no instructional delivery method demonstrates decisively different effectiveness compared to others under comparison; the weight of research indicates that technology can mediate instruction as effectively as traditional methods—at least when considering larger cohorts of students.

The purpose of this contribution is to draw attention not only to currently prevalent automatic approaches but also to evaluation of the readability and comprehensibility of specialized texts and above all to possibilities for identifying and, where appropriate, eliminating problematic content areas. For our research, we employ the current widely established eye-tracking technology. Because eye-tracking is well-documented and broadly applied across fields (neuroscience, marketing, education), literature offers numerous approaches and methods.

2 RELATED WORK

Instructional design in digital learning environments is commonly interpreted through the lens of cognitive load theory (CLT), which distinguishes between intrinsic, extraneous, and germane cognitive load. According to CLT, learning is optimized when instructional materials reduce unnecessary mental effort and free cognitive resources for schema construction. When design features do not directly support comprehension, they can increase extraneous load—the portion of working memory demands that does not contribute to meaningful learning—which diminishes the capacity available for processing core content [1], [2], [3]. Visual enhancements such as keyword highlighting and the inclusion of hyperlinks are often assumed to direct attention to important content and support navigation. However, CLT suggests that additional decision-making and navigational demands—for example, deciding whether to follow a link or integrating material across text segments—can increase extraneous load unless they are coherently integrated into the instructional structure. In the context of hypertext reading, the cognitive demands associated with link navigation and decision-making have been empirically linked to increased mental load and impaired comprehension relative to linear text [4], [5].

Despite the widespread use of hyperlinked and visually enhanced digital texts in educational settings, evidence for their learning benefits remains mixed. Studies suggest that design features that add surface-level visual elements may attract attention without facilitating deeper processing of conceptual content, especially if they introduce additional cognitive demands that compete with comprehension processes. Against this theoretical background, demonstrating an absence of improvement (a null effect) is not trivial: it provides theoretically meaningful evidence that superficial visual modifications—absent instructional integration that reduces cognitive load—may fail to enhance learning or even impose unnecessary cognitive costs [6].

The use of eye-tracking technology is grounded in the hypothesis that visual attention often reflects the reader's cognitive capacity to process textual content—i.e., reading with comprehension [7]. Contemporary eye-tracking technologies take various forms: devices integrated into displays; specialized external units mounted above the screen [8]; or eyewear equipped with cameras [9], [10], [11]. Increasing interest also surrounds the potential of standard webcams [12] found in most laptops, smart devices, and some PC monitors.

Healthy human eyes execute several types of movements with differing interpretations in psychology and neuroscience depending on context and combination.

The basic movements are fixations, saccades, and smooth pursuit. Fixations are intervals during which the reader's gaze is stationary—focused on a point for at least 200–300 ms. Saccades are short, rapid jumps of several tens of milliseconds between fixations; awareness of them is typically suppressed, with visual perception attenuated during the jump. Smooth pursuit occurs involuntarily and only when the eyes track a moving stimulus. Durations of fixations, counts and amplitudes of saccades, and combinations thereof provide valuable information for psychologists and other researchers [13] because empirically described relationships link these parameters to cognitive processes.

A specific combination of fixations and saccades is a regression—a backward jump in the text to the beginning of a word, sentence, or paragraph. The significance of the regressions remains an actively researched topic with contradictory interpretations (even within the same contexts) and mixed empirical results. Some studies [14], [15], [16] have identified positive correlations between certain regression types/metrics (e.g., counts for certain words, regression patterns); others [17], [18], [19] observed negative correlations, suggesting that readers with higher literacy have less need to reread passages (although potentially at the cost of skipping some content); still others found no correlation [20].

Within the framework of cognitive load theory, eye-tracking provides a valuable methodological bridge between instructional design and learners' cognitive processing. Visual attention patterns—such as fixation duration, number of fixations, saccadic transitions, and regressions—have been widely used as behavioral indicators of processing effort during reading. From a CLT perspective, increases in fixation time, frequent backward movements (regressions), or fragmented scan paths may reflect elevated extraneous cognitive load, as learners allocate additional resources to navigating or re-integrating information rather than constructing mental schemas. Consequently, eye-tracking enables an empirical examination of whether specific design features—such as keyword highlighting and hyperlinked navigation—facilitate learning by reducing unnecessary cognitive demands or, on the other hand, impose additional load that interferes with comprehension.

3 METHODOLOGY

In our previous research [21], [22], [23], we examined reading literacy (study materials delivered via LMS Moodle) when studying electronic materials versus classic paper form. We found no statistically significant differences between experimental and control groups (CGs)—neither in reading literacy (accurate comprehension of study-text content) nor in overall learning outcomes. Outcomes in both groups were obtained via a series of post-tests at semester end (compared with a pre-test at the beginning), with comparable performance in both cohorts. Consequently, subsequent experiments focused exclusively on electronically delivered materials.

All electronic materials were prepared according to contemporary study methodologies and indices (Flesch–Kincaid and Coh-Metrix). The Flesch–Kincaid index estimates text difficulty—i.e., how hard it is to comprehend specialized texts—and appropriateness for a given grade level. Texts were standardized in length and optimized with emphasis on the following feature set:

- Average sentence length
- Average syllables per word
- Proportion of long words

- Number of sentences in the text
- Average tokens per sentence (words, punctuation, and numbers within a sentence)
- Average characters per token
- Mistrík Index (Mistrík's lemmatization formula)
- Average word length
- Lexical density
- Lexical variability
- Index of morphological complexity
- Distribution of dependency tags
- Flesch Reading Ease
- Flesch–Kincaid Grade Level
- Automated Readability Index

Thus, the texts were carefully prepared to be manageable for students—a point confirmed in prior experiments. Nonetheless, in processing the results, we asked how, despite comparable literacy, students actually approached the materials. The experimental and CGs had essentially the same materials; the key difference was that the experimental group's texts contained images and visually highlighted hyperlinked keywords (defined using ChatGPT). Readers could clarify terms via a glossary or by navigating to a designated web page through the hyperlink. The Moodle Glossary module is a standard, and all interactions with it are logged as LMS activity records. This allowed us to count click-throughs from the educational text to hypertext and back—useful for examining possible correlations among highlighted keywords, fixations/saccades, and subsequent regressions and for assessing time efficiency in reading. The CG received the same texts with bolded keywords but without the conventional colored hyperlink highlighting that signals navigability. Based on prior results, we knew reading literacy did not markedly improve. We therefore posed the following questions for the present analysis:

1. Is there a difference in the minimum, maximum, and average number of fixations when reading the text versus images?
2. Do students, when encountering a highlighted keyword, actually use the hyperlink?

Experiments employed the Pupil Core eye-tracking device (see Figure 1), enabling precise measurement of ocular activity while reading [24], [25]. Pupil Core features two 120 Hz IR eye cameras (192 × 192 px) and one world camera (1920 × 1080 at 30 Hz or 1280 × 720 at 60 Hz). Recording was done using the open-source Pupil Capture application; post-hoc visualization and analysis used Pupil Player.

Fig. 1. Pupil core device, front and side views

Data generated by Pupil Capture are subsequently analyzed and visualized in Pupil Player (see Figure 2), providing precise information such as pupil-size changes, detected blinks, counts of fixations and saccades, and regressions.

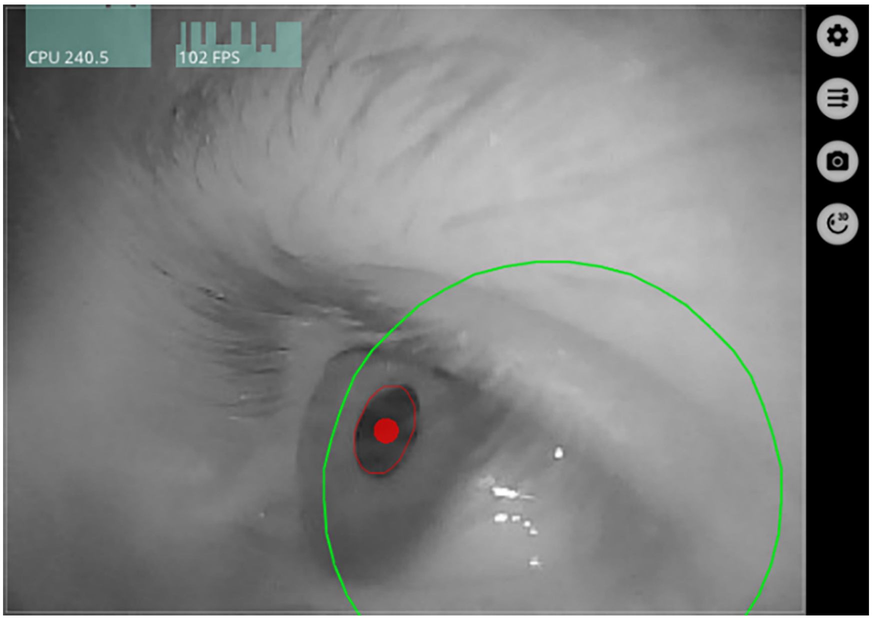


Fig. 2. Output from the eye-movement camera

4 DATA ACQUISITION PROCEDURE

A total of 80 first-year full-time students of applied informatics (bachelor level) were engaged for the experiment [21]. Students were randomly divide into two equally sized groups: an experimental group (EG) that accessed an e-course variant with visually distinguished key terms and a CG with the same subchapters and bolded keywords but no hypertext click-throughs. As reported earlier [21], 68 of 80 students participated across both measurements (12 did not, despite invitations). Of those, only 42 completed all measurements (consistently attending all sessions). To preserve group homogeneity, they were split evenly, 21 students per group. Although the final sample size ($n = 42$) is typical for eye-tracking experiments, it provides sufficient statistical power only for detecting medium-to-large effects (approximately *Cohen's* $d \geq 0.65$). The value of *Cohen's* $d \approx 0.65$ follows from a power analysis for the given sample size ($n = 42$, $21 + 21$), assuming $\alpha = 0.05$ and a desired statistical power of $1 - \beta = 0.80$ for a two-sample t-test. Given the sample size of 21 participants per group, statistical power was sufficient only for detecting medium-to-large effects. For a two-group comparison at $\alpha = 0.05$ and power $(1 - \beta) = 0.80$, the minimum detectable effect size is approximately *Cohen's* $d = 0.65$. Therefore, the absence of significant differences suggests that any potential effects of visual highlighting are likely smaller than this threshold. However, small effects of visual highlighting cannot be ruled out and should be examined in future studies with larger samples.

Students read two topics from an existing Slovak-language course. Each topic was reformatted to fit one screen without scrolling. The text area was marked using AprilTags [26], [27] so that Pupil Capture could define Areas of Interest (AOIs). A unique combination of three or more tags sufficed to mark an AOI; too few tags risked recognition failure, requiring manual AOI definition in Pupil Player (see Figure 3). The AprilTags used for defining AOI were applied exclusively for post-hoc processing in Pupil Player and were not visible to participants during the reading task; therefore, they could not have influenced gaze behavior.

The text was displayed on an LCD monitor, and for recording, we connected the Pupil Core eye-tracking device to relatively powerful PCs (Intel Core i7 and 8GB RAM) located in the test room (a standard classroom for teaching technical subjects). The individual phases of the experiment were carried out under the supervision of an experienced teacher.

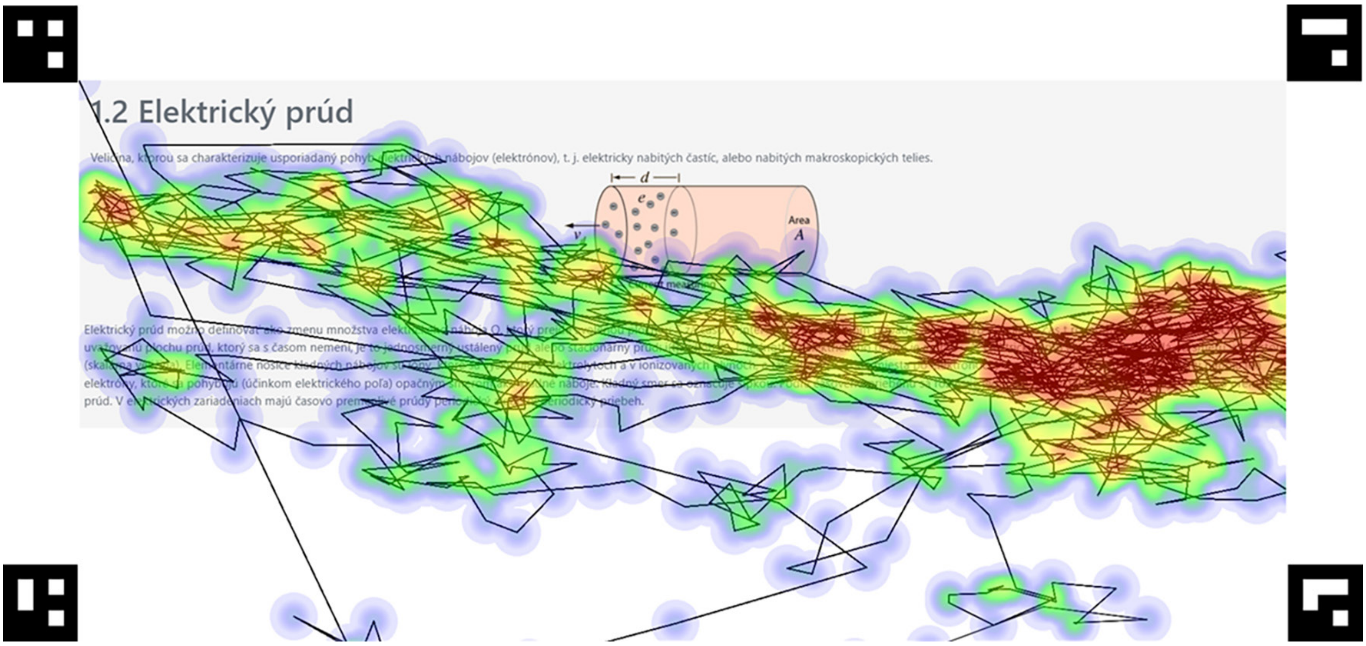
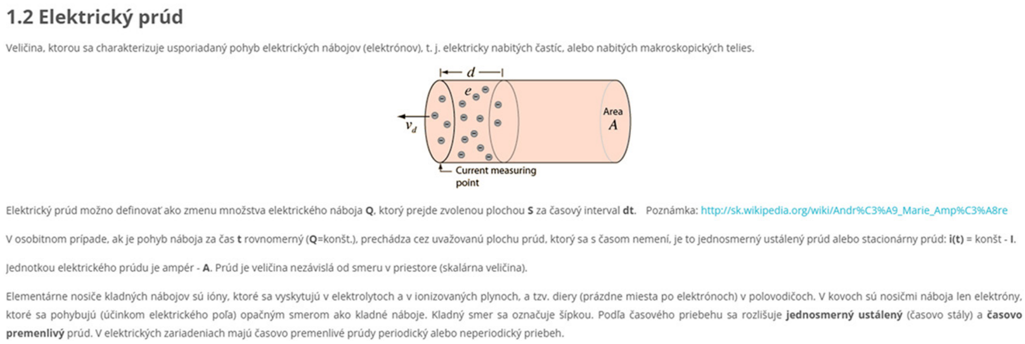


Fig. 3. Example of reading a chapter about the electric current topic (own creation)

Upon loading a recording, Pupil Player detects fixations and saccades, visualizes transitions, and exports all required data to CSV (e.g., durations and positions of fixations/saccades, fixation counts, and pupil movement in millimeters). This yields precise information for analysis. As we have shown (see Figure 3), the material elicited numerous fixations and saccades; fixations are also color-coded, with red denoting the highest density. Lines between fixations represent saccades—gaze shifts to new locations. Although the heatmap may appear chaotic, the CSV pinpoints not only counts but also timing, enabling a holistic view of how the participant processed the material.



1.2 Elektrický prúd

Veličina, ktorou sa charakterizuje usporiadaný pohyb elektrických nábojov (elektrónov), t. j. elektricky nabitých častíc, alebo nabitých makroskopických telies.

Elektrický prúd možno definovať ako zmenu množstva elektrického náboja **Q**, ktorý prejde zvolenou plochou **S** za časový interval **dt**. Poznámka: http://sk.wikipedia.org/wiki/Andr%C3%A9_Marie_Amp%C3%A8re

V osobitnom prípade, ak je pohyb náboja za čas **t** rovnomerný (**Q**=konšt.), prechádza cez uvažovanú plochu prúd, ktorý sa s časom nemení, je to jednosmerný ustálený prúd alebo stacionárny prúd: **i(t)** = konšt - **I**.

Jednotkou elektrického prúdu je ampér - **A**. Prúd je veličina nezávislá od smeru v priestore (skalárna veličina).

Elementárne nosiče kladných nábojov sú ióny, ktoré sa vyskytujú v elektrolytoch a v ionizovaných plynoch, a tzv. diery (prázdne miesta po elektrónoch) v polovodičoch. V kovoch sú nosičmi náboja len elektróny, ktoré sa pohybujú (účinkom elektrického poľa) opačným smerom ako kladné náboje. Kladný smer sa označuje šípkou. Podľa časového priebehu sa rozlišuje **jednosmerný ustálený** (časovo stály) a **časovo premenlivý** prúd. V elektrických zariadeniach majú časovo premenlivé prúdy periodický alebo neperiodický priebeh.

Fig. 4. Example of the study material the students read

Source: Authors' own.

As seen (see Figure 4), the text contains a hyperlink; the area around the link was expected to exhibit a high number of fixations.

5 MEASUREMENT RESULTS FROM THE FIRST READING OF THE TEXT

Our experiment entailed reading texts with identical content. Reading for the CG comprised a text without color-highlighted keywords accompanied by a relevant image. Reading for the EG used the same text and image; however, the keywords were provided as hypertext links.

Table 1 presents (refer to Table 1) the eye-movement results from the first reading of the text (T1). Neither the reading time nor the time spent on the image differs significantly. However, differences can be observed in the time spent on empty areas of the screen. This time is the lowest; thus, we may infer that both the text and the images engaged the readers. Whether this is in fact the case can be demonstrated by the number of fixations and regressions (refer to Tables 1 and 2).

Table 1. First reading of the text T1 – time spent on AOI

		Minimum	Maximum
Total Time [s]	*CG*	13.713	124.363
	EG	13.291	141.791
Reading Time [s]	*CG*	4.999	53.612
	EG	5.902	65.277
Time on the Image [s]	*CG*	8.714	59.605
	EG	7.389	51.515
Time Out [s]	*CG*	0	11.146
	EG	0	24.999

In Table 2, we can observe the average duration of fixations across all AOIs (refer to Table 2). As in Table 1, all values display a wide dispersion between maxima and minima (refer to Table 1).

Table 2. First reading of the Text T1 – average fixation durations

		Minimum	Maximum
Average Fixation Length [s]	*CG*	83.959	788.759
	EG	56.953	802.993
Average Fixation Length on Text [s]	*CG*	76.495	965.231
	EG	53.458	685.679
Average Fixation Length on the Image [s]	*CG*	97.102	897.745
	EG	61.716	610.300
Average Length of Fixation on an Empty Space [s]	*CG*	78.280	503.300
	EG	55.686	1113.000

The outlying value for the average duration of fixations on empty space is particularly noteworthy. Comparing the results in Tables 1 and 2, we find that despite the low time spent outside the text and image (empty areas of the screen), this area exhibits an almost identical average number of fixations (in both the control and experimental groups) as the average number of fixations on the text. By contrast, the average number of fixations on the image is slightly higher. At the same time, we can state that such an outlying value for the average number of fixations outside the text and image remains largely realistic, since fixations exceeding one second are not entirely uncommon (see Figure 5).

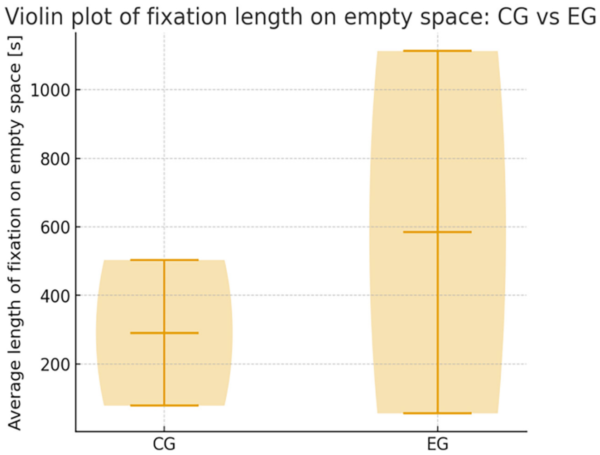


Fig. 5. Average fixation duration on empty space – first reading of the text

With regard to the counts of events in this text (refer to Table 3), we can observe an increase in the average number of fixations, particularly in connection with the image (refer to Table 2). This indicates that students devoted more attention to the image than to the text itself, even though the text contained highlighted keywords with hypertext functionality.

Table 3. First reading of the text T1 – counts of events

		Median	Mean	Std. Deviation	Shapiro-Wilk	P-Value of Shapiro-Wilk	Minimum	Maximum
Count of Fixation	*CG*	139.000	184.308	143.501	0.807	0.008	62.000	502.000
	EG	164.000	225.333	148.186	0.826	0.008	87.000	537.000
Text	*CG*	46.000	69.692	74.638	0.734	0.001	12.000	254.000
	EG	85.000	106.267	84.610	0.831	0.010	19.000	349.000
Image	*CG*	72.000	99.308	69.086	0.836	0.019	31.000	214.000
	EG	81.000	101.867	72.545	0.862	0.026	22.000	257.000
Empty Space	*CG*	10.000	14.538	12.353	0.868	0.050	0.000	34.000
	EG	10.000	17.667	34.690	0.483	< .001	0.000	140.000
Regressions	*CG*	18.000	21.923	19.423	0.729	0.001	1.000	80.000
	EG	18.000	44.800	65.434	0.642	< .001	3.000	253.000
Transitions	*CG*	0.000	4	7.981	0.607	< .001	0.000	24.000
	EG	1.000	7	12.671	0.662	< .001	0.000	46.000

To explicitly visualize the null result (see Figure 6), we plotted mean differences (EG – CG) with 95% confidence intervals based on the reported group means, standard deviations, and sample sizes ($n = 21$ per group). We additionally displayed standardized effect sizes (Hedges g) with approximate CIs and $a \pm 0.2$ equivalence band (small effect-ROPE). This estimation plot highlights that all effects are near zero and their CIs cross zero, consistent with the absence of statistically and practically meaningful differences.

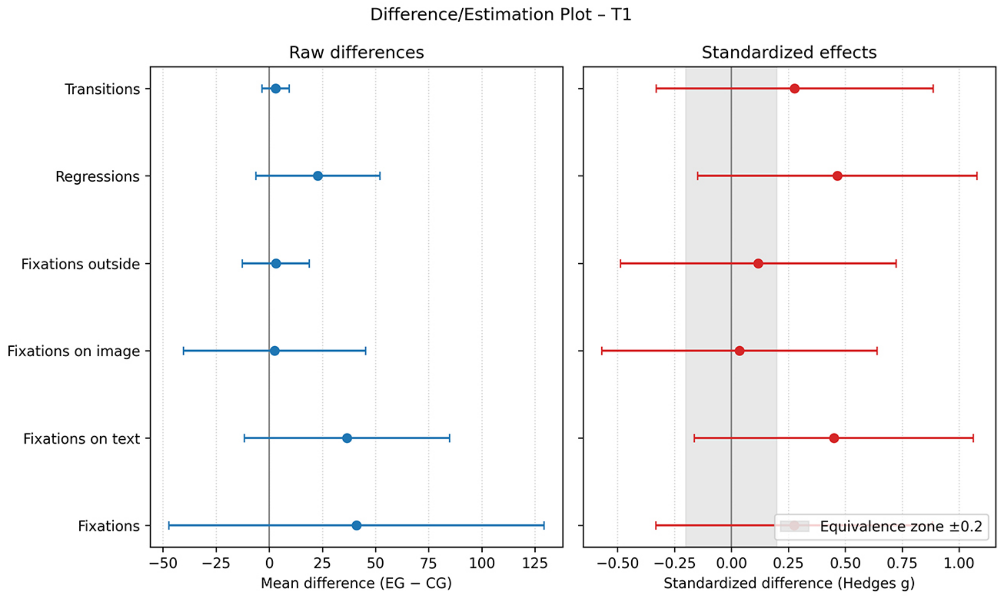


Fig. 6. Difference/estimation plot for the first reading (T1) comparing the experimental (EG) vs. the control group (CG) across eye-tracking metrics

It is interesting that neither the experimental nor the CG made substantial use of the hypertext link option, i.e., transitions (see Figure 7). The number of transitions is very low in both groups: an average of seven clicks in the EG and only four clicks in the CG. We can conclude that, despite having the option of hypertext at the highlighted keyword, students used this form of navigation only to a limited extent.

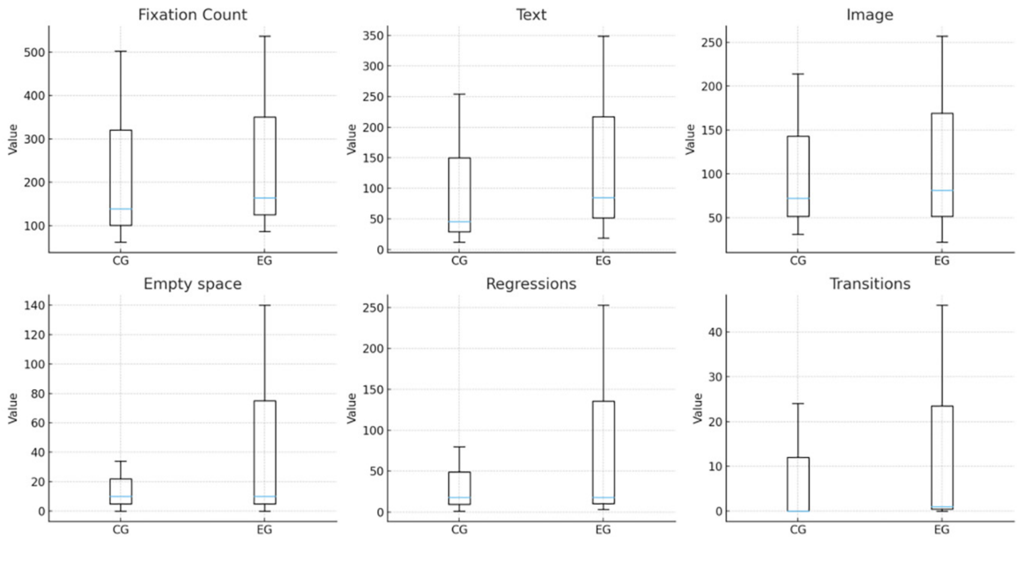


Fig. 7. Summary graphical representation of relationships between CG and EG – first reading of the text

We can also observe (see Figure 7) a fairly large increase in the mean maximum number of regressions between EG and CG, as well as an increase in fixations on empty space in EG.

This means that both groups made only minimal use of the hypertext option. However, according to the number of regressions, students returned several times to the same place and refixated on it. The largest number of regressions (a total of 253) was recorded in the experimental group (see Figure 7).

6 MEASUREMENT RESULTS FROM THE RE-READING OF THE TEXT

As in the first reading of the text (T1), there are no very large differences upon re-reading after two weeks (hereafter denoted T2) that could be unequivocally attributed to changes in the highlighting of important technical terms. As documented by other work in this research area [28], [16], [29], [30], repeated reading alone can strongly influence reader behavior, even when readings are separated by several days or weeks. In Table 4, however, we see that the difference between the time needed for reading (minimum and maximum) in both groups (CG and EG) is not very pronounced (refer to Table 4).

Table 4. Re-reading of the Text T2 – time spent on AOI

		Minimum	Maximum
Total Time [s]	*CG*	6.967	124.064
	EG	14.269	132.13
Reading Time [s]	*CG*	2.174	48.885
	EG	2.653	53.603
Time on the Image [s]	*CG*	4.793	66.138
	EG	11.616	63.726
Time Out [s]	*CG*	0	9.041
	EG	0	14.801

At the same time, in the CG we observe a slight decrease in the time spent viewing the image, which is not caused by an increase in the time spent looking at empty space, as we do not record any increase there that would be sufficiently pronounced to explain the difference (the difference between minimum and maximum in the "Time out" parameter).

Fixations exceeding 2000 ms were excluded from analysis, as such values are indicative of tracking loss or calibration artifacts rather than genuine visual processing. In addition, gaze samples falling outside all defined AOI were removed. These criteria were applied uniformly across participants and conditions.

After excluding these extremes, the values remaining in Table 5 are in line with our expectations.

Table 5. Re-reading of the text T2 – average fixation durations

		Minimum	Maximum
Average Fixation Length [s]	*CG*	60.722	486.531
	EG	55.388	677.097
Average Fixation Length on Text [s]	*CG*	74.207	451.931
	EG	62.031	859.000
Average Fixation Length on the Image [s]	*CG*	72.959	799.892
	EG	53.732	690.625
Average Length of Fixation on an Empty Space [s]	*CG*	35.000	207.769
	EG	50.400	481.667

Compared to T1, we recorded in both groups a shortening of the maximum value of the average overall fixation duration and of the maximum value of the average duration of fixations outside the text and image (empty areas of the screen).

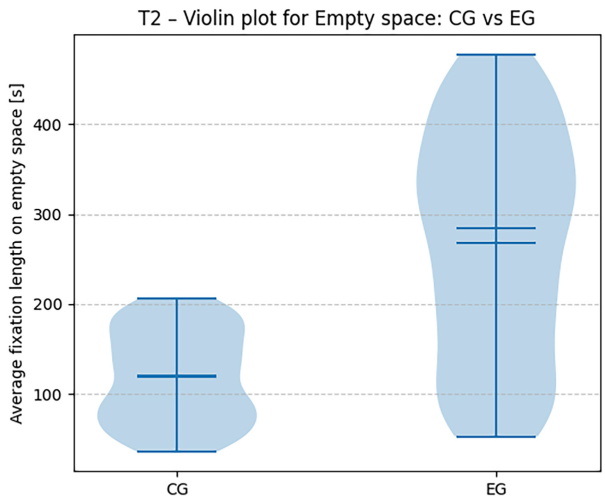


Fig. 8. Average Fixation Duration on Empty Space – Second Reading of the Text

Based on the results in Table 5, we may therefore presume that the students focused more on the text and the image (refer to Table 5 and see Figure 8).

Table 6. Re-reading of the Text T2 – Counts of Events

		Median	Mean	Std. Deviation	Shapiro-Wilk	P-Value of Shapiro-Wilk	Minimum	Maximum
Count of Fixation	*CG*	166.500	169.000	75.500	55.000	109.000	82.000	3.000
	EG	223.143	210.933	97.929	99.200	112.429	96.133	12.500
Text	*CG*	139.425	131.948	75.318	90.812	70.347	65.643	19.876
	EG	0.875	0.927	0.862	0.858	0.923	0.887	0.684
Image	*CG*	0.049	0.242	0.033	0.023	0.243	0.061	< .001
	EG	46.000	51.000	20.000	3.000	17.000	26.000	0.000
Empty Space	*CG*	488.000	490.000	268.000	298.000	293.000	242.000	64.000
	EG	166.500	169.000	75.500	55.000	109.000	82.000	3.000
Regressions	*CG*	223.143	210.933	97.929	99.200	112.429	96.133	12.500
	EG	139.425	131.948	75.318	90.812	70.347	65.643	19.876
Transitions	*CG*	0.875	0.927	0.862	0.858	0.923	0.887	0.684
	EG	0.049	0.242	0.033	0.023	0.243	0.061	< .001

To explicitly visualize the null result (see Figure 9), we plotted a difference/estimation plot for the re-reading (T2) comparing the experimental (EG) vs. the CG across eye-tracking metrics. The left panel shows mean differences (EG – CG) with 95% confidence intervals and a vertical zero line; point estimates close to zero with intervals crossing zero indicate negligible differences. The right panel shows standardized mean differences (Hedges' g) with 95% confidence intervals; the shaded band denotes an equivalence zone (±0.2, small effect), emphasizing practical non-difference.

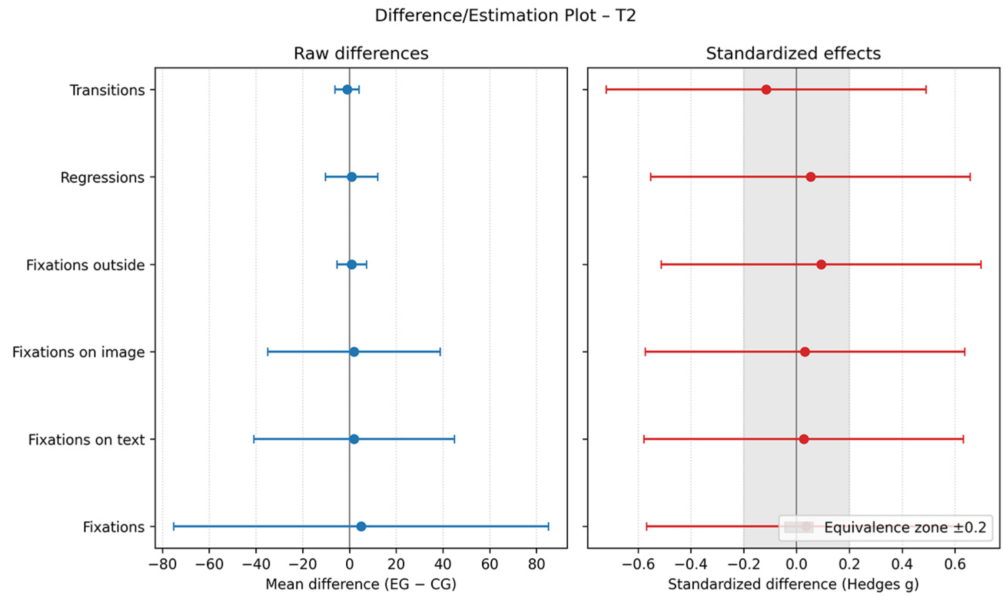


Fig. 9. Difference/estimation plot for the re-reading (T2) comparing the EG vs. the CG across eye-tracking metrics

Additionally, the results show (refer to Table 6 and see Figure 10) an anomaly whereby the control group, unlike the experimental group, used transitions more extensively despite the lack of color highlighting (see the maximum or mean). The number of regressions, however, is almost identical in both groups in terms of the mean as well as the minimum and maximum. This means that although the control group used the hypertext option (even though it was not color-highlighted and thus may not have attracted attention), its behavior in terms of regressions was entirely comparable to that of the experimental group.

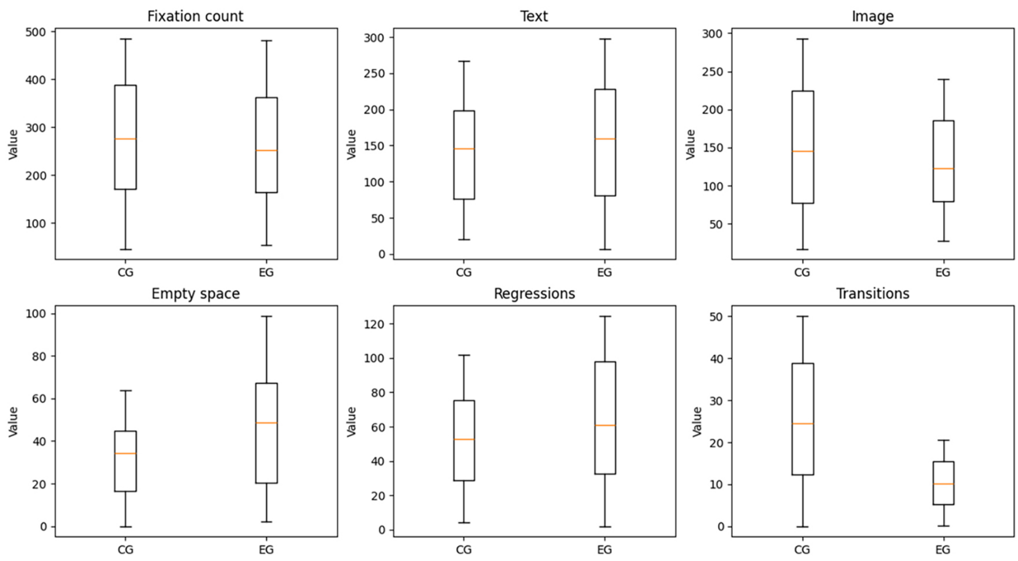


Fig. 10. Summary graphical representation of relationships between CG and EG – re-reading of the text

7 OVERALL EVALUATION OF THE RESULTS

With respect to our research questions, we did not succeed in demonstrating an effect of visually distinguishing important terms in the lessons. We can state that students made only minimal use of the hypertext option when a keyword was highlighted. Differences between students assigned to the control and experimental groups were neither consistent nor statistically significant. In the first reading, students returned several times to the same place and re-fixated on it (maximum number of regressions: 253). Upon re-reading the same text after an interval of two weeks, the number of fixations decreased, and the number of regressions in both groups became balanced. This indicates that the text was already more comprehensible to the students and therefore did not require as much focused attention as at the beginning (during the first reading).

The inclusion of estimation plots (see Figures 6 and 9) strengthens the interpretation of our null findings. While traditional tables and box plots summarize group means, they do not clearly convey the practical significance of differences. Estimation plots explicitly visualize the uncertainty around mean differences and standardized effect sizes, highlighting that all confidence intervals cross zero and most estimates fall within an equivalence zone (±0.2). This representation aligns with current recommendations for transparent reporting of null results, emphasizing that the absence of statistically significant differences is not a methodological failure but an informative outcome. By showing both raw and standardized differences, these plots help readers assess whether any observed variation is likely to be educationally meaningful. In our case, the visualization confirms that highlighting keywords and adding hyperlinks produced negligible effects on reading behavior and comprehension, reinforcing the conclusion that superficial design changes are insufficient without deeper structural integration.

Topics similar to those we focused on in our research conducted over the last four years [31], [23], [22] are, in several respects, developed and complemented by the results of other scholars publishing in this area [32], [33], [34]. Despite unexpected complications caused by the SARS-CoV-2 pandemic and subsequent counter-pandemic measures, we were able to adjust our methodology and continue our work. These modifications, however, are associated with measurement imprecision and constraints on the metrics we were able to record.

A range of studies [35], [36], [37], [38] have addressed the effect of images on text comprehension. They found that unrelated images (advertising banners) can not only distract readers, but also induce more regressions in the text, slow overall reading by shortening saccades, and prolong individual fixations. They did not, however, find a significant difference in information retention across experimental and control groups. Our work examined the visual distinction of keywords. Unlike those authors, we did not find any significant effect of such a modification of text appearance on student behavior.

Ariasi et al. [39] provided evidence more than a decade ago [40] that text structure influences the distribution of students' attention [41]. In our study, we compared the results of the experimental and control groups when reading a text that had the same structure for both groups but differed visually by hypertext links and highlighted keywords. Whereas Hunsu et al. [41] and Asberger et al. [42] suggest that changing the sub-structure can have a positive benefit, our results make it clear that such changes must encompass the overall structure. Highlighting only keywords and marking them as hypertext links does not yield the desired effect.

Sample sizes reported in eye-tracking experiments are particularly noteworthy for comparison. For example, Reimlinger et al. [43] worked with only 17 subjects in their study (experts 7, novices 10), as they were constrained by the time and resources required by specialized hardware. Although at the outset of our experiment we intended to include a total of 80 students, the research sample was reduced to roughly half—42 (21 in each group). Similar to Zhu et al. [44], who worked with only 24 participants (12 in the control group + 12 in the expert group), we too—despite a relatively small sample (which can sometimes be limiting)—were able to identify a difference in the subjects' ability to locate the required information in a schematic representation. This demonstrates the power of the technology even with smaller sample sizes.

Numerous studies—Ehrhart et al. [45], Arts et al. [46], Schewior et al. [47], among others, and also Lindner et al. [48], [49]—investigated the influence of images, text, and highlighted parts of text. They sought to demonstrate that learning from study materials combining text and illustrations has a positive effect on memorization and thus subsequently reduces the total time needed to re-study the same text. Based on our results, we can state that if texts are methodologically sound and an appropriate level of reading literacy is ensured, the time required for re-studying the same text can indeed decrease.

In further research, following Ponce et al. [50], González-Diez [51], and Leng et al. [52], we intend to focus on verifying whether there is a correlation between regressions and long-term knowledge retention. That is, to determine unequivocally how the number of regressions in educational texts affects students' overall outcomes, for example, at the end of a semester.

The results of our study showed that highlighting keywords as hypertext links had no significant impact on students' reading behavior or comprehension. Hyperlinks were rarely used, and attention was directed primarily toward images rather than the text itself. At first glance, these null findings might seem unremarkable; however, when interpreted through the lens of established theories and the characteristics of today's learners, they yield important insights.

From the perspective of cognitive load theory (Sweller [53]), students' limited use of hyperlinks suggests that additional navigation options may introduce extraneous load without delivering meaningful benefit. If learners already struggle to manage essential information, clickable keywords may function more as a distraction than a learning aid. In this sense, our results align with findings that unnecessary design features can impair learning by overloading working memory.

According to Mayer's multimedia learning principles [54], students learn most effectively when text and visuals are integrated in a coherent and complementary manner. In our study, images clearly attracted more attention than text. This reflects Mayer's modality principle (dual-channel processing) but also highlights a possible misalignment: when images dominate but are not fully integrated with textual explanation, learners may form superficial impressions of understanding rather than deep comprehension.

This interpretation is consistent with recent research on digital reading behavior [55], [56], which shows that readers of online materials tend to scan visually salient elements at the expense of sustained engagement with linear text. Our results, therefore, resonate with the broader debate about whether digital learning environments encourage shallow rather than deep reading.

The generational context is also important. The current cohort of undergraduates experienced secondary education during the COVID-19 pandemic, a period marked by heavy reliance on online platforms. This generation is accustomed to having virtually unlimited access to ICT tools, information, and media [57]. Yet, paradoxically, they often struggle to process information critically and sustain attention. Studies on digital learning fatigue show that attention declines sharply after approximately 30 minutes of continuous input [58]. In our findings, students' prioritization of images over text mirrors this broader tendency: quick visual cues are perceived as sufficient for comprehension, even when the underlying textual information contains the actual conceptual detail.

By contrast, earlier generations of students using printed study materials typically relied on active strategies such as highlighting or annotating text [59], [60], [61]. In such contexts, visual emphasis was strongly associated with importance: what was marked in the text was consciously remembered. Our results indicate that current students no longer follow these conventions. For them, visual salience does not automatically signal relevance; rather, it competes with other stimuli (e.g., images, videos, animations) in a crowded digital environment.

Based on these findings, we argue that instructional design should not assume that visual highlighting alone will direct student attention effectively. Instead, more comprehensive structural approaches are required, such as text design [62], explicit text–picture integration training [52], or coherence-based multimedia design [63].

8 CONCLUSION

Based on the conducted experiment, we can state that visually highlighting keywords and linking them to hypertext did not have a significant effect on readers' behavior or on their level of text comprehension. Participants in both groups used hypertext only minimally, and the differences between the CG and EGs were neither consistent nor statistically significant. Students' attention was more focused on images than on the text, with a higher number of regressions during the first reading that then declined on re-reading. This suggests that comprehension of the content improved over time, albeit independently of visual highlighting. The results support the claim that text quality and its methodological preparation play a more significant role than the mere form of visual highlighting. For future research, we recommend verifying the correlation between regressions and long-term knowledge retention, as well as examining the effectiveness of more comprehensive structural modifications of the text.

This study demonstrated that visual highlighting of keywords, implemented as hypertext links, did not significantly affect reading patterns or comprehension among undergraduate students. Both experimental and control groups used hypertext minimally, and attention was consistently drawn more to images than to text. These findings contribute to the ongoing debate about the effectiveness of multimedia design in education by showing that superficial visual modifications, without deeper structural adjustments, are unlikely to enhance learning.

The null results should not be interpreted as a failure but rather as evidence that instructional design must go beyond "cosmetic" interventions. In the context of post-COVID student cohorts, who are heavily exposed to digital media yet often experience shortened attention spans and surface-level engagement, designers of educational materials face particular challenges. Visual salience alone does not guarantee learning; students may perceive that they have "understood" a concept simply by viewing an image or animation, even while neglecting the explanatory text.

For practice, our findings suggest three implications:

1. Prioritized coherence over decoration: Visual elements must be meaningfully integrated with text to reduce extraneous cognitive load and support deep comprehension.
2. Support active processing: Encourage learners to engage in annotation, summarization, or guided highlighting, restoring some of the effective strategies of earlier generations in a digital form.
3. Adapt to generational attention patterns: Instructional materials should be structured into shorter, interactive segments to reflect current students' limited sustained attention while still promoting critical engagement with text.

Our results confirm that the pedagogical challenge of the digital age lies not in providing ever more visual stimuli, but in designing learning environments that align with cognitive principles and foster deliberate, reflective reading. Highlighting and hyperlinks alone cannot replace coherent instructional design.

9 STATEMENTS AND DECLARATIONS

The authors declare no conflicts of interest. This study was approved by the Ethics Committee, number UKF/556/2024/191013:002. The authors confirm that all subjects provided appropriate informed consent and that details of how this consent was obtained are specified in the manuscript.

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9.2 Conflict of interests

Each named author has substantially contributed to conducting the underlying research and drafting this manuscript. Additionally, to the best of our knowledge, the named authors have no conflict of interest, financial or otherwise.

9.3 Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) did not use generative AI and AI-assisted technologies except basic tools for checking grammar and spelling.

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