Using an eye tracker to examine the effect of prior knowledge on reading processes while reading a printed scientific text with multiple representations

Article *in* International Journal of Science Education · May 2022

DOI: 10.1080/09500693.2022.2072013

Yu-Cin Jian
National Taiwan Normal University

Routledge
Taylor & Francis Group

International Journal of Science Education

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tsed20

Using an eye tracker to examine the effect of prior knowledge on reading processes while reading a printed scientific text with multiple representations

Yu-Cin Jian

To cite this article: Yu-Cin Jian (2022): Using an eye tracker to examine the effect of prior knowledge on reading processes while reading a printed scientific text with multiple representations, International Journal of Science Education, DOI: 10.1080/09500693.2022.2072013

To link to this article: https://doi.org/10.1080/09500693.2022.2072013

Published online: 15 May 2022.

INTERNATIONAL JOURNAL OF SCIENCE EDUCATION
https://doi.org/10.1080/09500693.2022.2072013

Using an eye tracker to examine the effect of prior knowledge on reading processes while reading a printed scientific text with multiple representations

Yu-Cin Jian

Department of Educational Psychology and Counseling, National Taiwan Normal University, Taipei, Taiwan

ABSTRACT

Readers' prior knowledge is an important factor for comprehending scientific texts. The study used an eye tracker to examine the reading processes of the undergraduates with high (HPK) and low prior knowledge (LPK) while reading a long printed scientific article. The results of measuring the eye movements offered some interesting findings. First, HPK readers are more capable of using multiple representations and know the importance of scientific diagrams for reading comprehension; the results revealed that HPK readers spent significantly longer fixation durations on representational and statistical diagrams and had higher percentages of transitional fixations between text and diagrams than did LPK readers. Second, LPK readers were much more text-driven; the total fixation durations on text was significantly higher for the LPK readers than for the HPK readers, and they also exhibited a tendency to read the diagram captions rather than the diagrams after reading the text. Third, mature readers in both groups would engage in self-regulating their reading strategy to slow down their reading speed for processing more important information. This study overcame technical limitations and recorded readers' eye movements in a real print reading situation which may open the path to assess broader issues in future reading research.

ARTICLE HISTORY
Received 4 August 2021
Accepted 26 April 2022

KEYWORDS
Eye movements; prior knowledge; reading processes; scientific text; multiple representations

Kintsch's (1988, 2005) construction-integration (CI) model emphasises the role of prior knowledge on reading comprehension. The CI model explains that it is insufficient for the construction of a coherent mental representation of the situation depicted by the text but requires readers' prior knowledge to integrate into an effective situation model for reading texts. In support of this argument, empirical evidence has confirmed the significant influence of prior knowledge on reading comprehension (Cromley et al., 2010; Ozuru et al., 2007) and that it is a strong indicator of predicting reading comprehension (McCullough, 2013) even when readers' grade level, decoding ability, listening comprehension, and oral vocabulary are controlled (Talwar et al., 2018).

CONTACT Yu-Cin Jian jianyucin@ntnu.edu.tw Department of Educational Psychology and Counseling, National Taiwan Normal University, No. 129, HePing East Road, Section 1, Taipei, Taiwan

These above-mentioned studies have used standardised tests to assess learning outcomes. However, it remains unclear how readers' prior knowledge dominates the cognitive attention they pay to certain information in the text such that their old and new knowledge is integrated. Examining the possible differences in the reading processes for high prior knowledge (HPK) and low prior knowledge (LPK) readers may help us understand the underlying mechanism. The reading process is a latent construction for reading comprehension, and one way to examine the reading process is by monitoring readers' eye movements. The eye movement behaviour is observed in the reading process. Therefore, the manifestation and quality of the reading process are quantified via eye-tracking metrics since eye trackers can provide adequate indicators that reflect moment-to-moment cognitive processing during reading in real-time (Miller, 2015; Rayner, 1998). Most of the research on reading and eye movements used sentences (Chaffin et al., 2001; Juhasz & Rayner, 2003; Williams & Morris, 2004) or pure texts (Ariasi et al., 2017; Chen & Chen, 2020; Foster et al., 2018; Jian & Ko, 2014; Jian et al., 2013) as reading material and have identified some basic characteristics of eye movements in information processing. For example, people's eyes usually remain relatively still during 'fixations' for about 200–250 milliseconds to process the information being conveyed by words, whereas people continuously make eye movements (called 'saccades') during reading to bring a new region of text into the fovea of eyes for detailed analysis. The average saccade size is 7–9 English letter spaces; people regress backwards to read the information that was previously seen while reading comprehension suffered. The proportion of regressive saccades has been found to be about 10–15% in a reading episode (cf., a 20-year review paper; Rayner, 1998).

Texts in science, technology, engineering, and mathematics (STEM) heavily rely on a variety of multiple representations (e.g. words, diagrams, photos, tables) to illustrate complex concepts (Ainsworth, 2006; Rau, 2018). Previous research has revealed that multiple representations in scientific articles do not ensure good reading comprehension for all readers (Guo et al., 2020; Renkl & Scheiter, 2017). Examining the processes of science reading may help explain how unsuccessful reading comprehension occurs. In the past decade, a few studies have investigated the reading processes of illustrated scientific text through eye tracking (Eitel, 2016; Jian, 2018, 2019, 2020; Mason et al., 2013; Scheiter & Eitel, 2015; Schüler, 2017) and have offered some interesting findings. For example, when reading scientific illustrated texts, readers are text-driven, regardless of whether they are adults (Hegarty & Just, 1993; Ho et al., 2014; Jian, 2018, 2019; Tsai et al., 2019; Yang et al., 2016) or young people (Jian, 2016, 2018; Wu et al., 2021). That is, readers tend to focus more cognitive attention (reflected by the eye-movement indicator of having a larger proportion of fixation durations) on the text than the diagrams during scientific illustrated text reading. Previous research has also found that mature adult readers are more capable of using diagrams (i.e. decode diagram information, make references of text and diagram) to help comprehend what they are reading than are amateur young readers (Jian, 2016). However, research that uses eye trackers to investigate the effect of prior knowledge on illustrated text reading processes is scarce (Ho et al., 2014).

In addition, all the above-mentioned studies were conducted by presenting the reading materials on computer monitors rather than as printed material. Although the reading process of print and digital media may share some commonalities, they might also involve some unique processes. For example, undoubtedly, reading is an interaction of bottom-up and top-down processes (Kintsch, 1988, 2005; Mayer, 2005; Schnotz, 2014; Schnotz & Bannert, 2003) regardless of whether print or digital reading conditions are involved; however, the mental engagement and reading comprehension degree may different between these two reading conditions (cf., a review; Singer & Alexander, 2017).

Moreover, given the limitations of screen size and eye-tracking analysis technology in the past years, previous studies have used articles with relatively few pages (referred to as short articles henceforth) (e.g. one page displayed on the screen) as reading materials instead of articles with several pages (referred to as long articles), which were similar to the reading experiences in our daily lives, particularly for scientific text reading. With significant technical progress, these limitations have been resolved to some extent. To increase the ecological validity, this study used a long printed scientific text with complex multiple representations (i.e. words, photos, representational, interpretational, and statistical diagrams) as the reading material and aimed to gain a better understanding of how readers' prior knowledge influences the eye-movement patterns when reading printed material.

The role of prior knowledge according to reading theories

Reading is the process of interpreting and extracting meaningful information from text (Kintsch, 1988, 2005; McNamara et al., 1996). Readers' prior knowledge significantly influences how textual meanings are interpreted. According to both general reading comprehension theories (e.g. CI model, Kintsch, 1988, 2005; Kintsch & Van Dijk, 1978) and text-and-diagram reading theories (e.g. Cognitive Theory of Multimedia Learning (CTML), Mayer, 2005; Integrated Model of Text and Picture Comprehension, Schnotz & Bannert, 2003; Schnotz, 2014), prior knowledge plays a very important role in reading comprehension.

Among general reading comprehension theories, the CI model (Kintsch, 1988, 2005) is extremely influential in reading comprehension theory. This model states that the activation and utilisation of knowledge stored in readers' long-term memory greatly influences reading comprehension. Specifically, it is concerned with how readers put individual textual propositions together and construct an entirety and a coherent mental model. Kintsch regarded the final mental model is a concept of network consisting of two operation circles of 'construction' and 'integration.' Among these, construction is a bottom-up process. Readers first perform word recognition to understand superficial textual concepts. They then organise these concepts into propositions (a proposition is the smallest processing unit in textual reading) and organise several propositions to gradually enlarge the processing units of information and enrich their knowledge network. Integration, on the other hand, is a top-down process. Readers use prior knowledge and experience schema from the long-term memory to connect their old knowledge and the new information being received in the present reading moment and to regulate and integrate the old and new information to form a more complete mental model of a text. In construction, multiple propositional representations, which are relevant, irrelevant, or redundant with respect to the text will activate in the reader's mind. Therefore, it is necessary to limit the activated contents, which rely on top-down integration process. This process emphasises merging relevant propositional representations with the main point of the text and eliminating the irrelevant and redundant representations from the reader's mind. Through this concept of 'activation-limitation,' the CI model theorises reading as an interaction of bottom-up and top-down processes.

Theories of multimedia learning that also strongly emphasise background knowledge have significantly impacted reading and learning. CTML (Mayer, 2005) proposes that text-and-diagram reading involves three cognitive processes: (1) *selection* of relevant information, which occurs at the moment while readers focus their attention on specific words and diagrams. This process brings external representations into readers' working memory; (2) *organising* the selected textual (or pictorial) information into a larger concept of textual (or pictorial) representation. This process involves encoding external representation into internal representation; (3) *integrating* the organised textual and pictorial information and readers' prior knowledge to construct a mental model. This process involves activating readers' prior knowledge in the long-term memory and bringing it into working memory for utilisation. Prior knowledge, thus, appears to play a crucial role in effective reading comprehension.

Although all the discussed reading theories agree that reading is an interaction of bottom-up and top-down processes, top-down processes have not received adequate attention (Duke et al., 2004; Tarchi, 2010). The present study aims to address this research gap.

Prior knowledge's influence on eye movements and reading comprehension of scientific text

In recent years, empirical research has gradually investigated the role of prior knowledge on scientific text reading. Cromley et al. (2010) used structural equation modelling to examine the relationships among several variables (e.g. inference, reading comprehensions strategies, reading vocabulary, word reading, and prior topic knowledge) and reading comprehension. They asked undergraduates to read scientific texts and complete a reading comprehension test. These participants included freshmen, juniors, and seniors who majored in biology. The results showed that readers' prior knowledge had by far the largest effect on comprehension; its significant direct effect was .345, and it also had indirect effects via reading strategies and inferences, with a value of .281 for total indirect effects. Tarchi (2010) also found that prior knowledge played a central role in reading comprehension for middle-school students through direct influence and indirect mediation. In another empirical study, Kohl and Finkelstein (2008) found that first-term physics students were less skilled at using multiple representations than were physics graduate students. The former were more likely to meander across different representations during problem solving, with no clear purpose for their use.

Regarding the influence of prior knowledge on eye movement during scientific text reading, interesting findings include those by Cook et al. (2008), who used an eye tracker to investigate how HPK and LPK senior-high school students viewed and explained diagram contents about cellular transport. The results found that HPK students had longer fixation durations on thematically relevant contents included in the biological diagrams. This was because they have schema of the specific knowledge and are capable of connecting and integrating new and old knowledge to enlarge their knowledge network.

However, LPK readers focused on the surface features (e.g. different colours) of the biological diagrams to construct their science knowledge because they relied more on a bottom-up process, that is, reading external information provided by the learning material, rather than the top-down process of knowledge guidance. Ho et al. (2014) used an eye tracker to investigate how HPK and LPK undergraduate students read a one-page scientific report on a website. This report described the relationship between global climate change and the greenhouse effect and provided two data diagrams demonstrating the changes in atmosphere and temperature during the last 200,000 years. The results found that HPK readers spent longer fixation durations and made more regressions on the diagrams than did LPK readers. Moreover, the HPK readers not only made more eye transactions between textual and pictorial sections but also between the two data diagrams than did LPK readers. These results indicated that HPK readers were capable of decoding and organising diagrammatic information, as well as integrating the information provided by multiple representations for reading comprehension.

Summarising, these above-mentioned studies have clarified how HKP and LKP readers process short scientific articles on the screen monitor (Ho et al., 2014; Jian & Ko, 2014). However, most scientific articles for adult readers are long and contain multiple representations. Therefore, this study used an eye tracker to examine how HPK and LPK readers read a long scientific article with multiple representations in a print reading situation. The following research questions were formulated:

RQ1: Do HPK readers exhibit better recall and reading comprehension than LPK readers while reading a long science article?

RQ2: Do HPK readers had different eye movements from LPK readers while reading a long science article?

RQ3: To what extent do prior knowledge and reading material (chart types, article pages, etc.) influence gaze behavior.

RQ4: Do HPK and LPK readers used different reading strategies (reflected by the sequences of eye fixations) while reading the long science article?

Methods

Participants

Participants were 49 undergraduate students recruited from XXX University. Among them, 25 participants (11 males and 14 females) who had majored in geography or earth science had HPK of the learning material (the topic was typhoons and earthquakes). Their mean age was 21.08 years (*SD* = 2.01). A total of 24 participants (10 males and 14 females) who had majored in education, liberal arts, technology, and engineering had LPK et al. Their mean age was 21.33 years (*SD* = 1.88). All the participants were native speakers of the language used in the learning materials and had normal or correct-to-normal eyesight.

Materials

The materials consisted of a consent form, a prior knowledge test, a questionnaire on epistemic beliefs in science, learning material, and a reading test for evaluating the learning outcome. The prior knowledge test consisted of 10 multiple-choice questions measuring knowledge about basic concepts of typhoons and earthquakes. All the test items were collected from middle-school scientific textbooks to ensure that the undergraduate participants were familiar with these concepts. The quality and correction of the test items were confirmed by two middle-school teachers who taught earth science and had a master's degrees in science. Each correct answer was awarded a score of one, and the maximum score was ten. The questionnaire on epistemic beliefs in science was mainly adopted from Conley et al. (2004) and Yang et al. (2016). This questionnaire contained 26 items and needed to be answered on a five-point scale ranging from 1 ('strongly disagree') to 5 ('strongly agree'). Examples include 'Everyone needs to believe what scientists say,' 'The most important thing in doing science research is to find the unique right answer,' and 'Doing experiments is a good way to confirm a scientific idea.' Among the questionnaire items, items 1–11 were reversed and were scored accordingly.

The learning material (see Figure 1) was a six-page science article from the magazine *Scientific American* (Liu, 2009). The topic of this science article was slow earthquakes triggered by typhoons. It consisted of text (introduction, paragraphs of subtitles 1–4); eight diagrams (three decorative, two representative, one explanatory, and three statistics); and diagram captions. The text was divided into hierarchical sections and sub-sections. The introduction paragraph introduced typhoons and earthquakes as the two main natural disasters in Taiwan, Subtitle 1 paragraph discussed dark energy in an earthquake, Subtitle 2 paragraph discussed the slow earthquake discovered in Taiwan, Subtitle 3 paragraph explained how typhoons produce slow earthquakes, and Subtitle 4 paragraph clarified that the reason was pressure changes.

The reading test on the learning material consisted of the following six essay questions: one free-recall question ('Please recall the article content as much as possible'), one main idea question ('What is the main idea of this article?'), and four open-ended questions ('Please explain what a "Slow Earthquake" is and describe its characteristics'; 'Please explain why the displacement velocity of eastward (the seaside) Taiwanese mountains is higher than that of the west (the longitudinal valley) by about two centimetres of the Taiwan mountains, but the number of Felt Earthquakes in the east is less than in the western longitudinal valley'; 'The earthquake frequency and Richter magnitude scale of eastern Taiwan are lower than Japan, but the relative reduction of the plate is higher than that of Japan, reaching 8 cm per year. Does this energy disappear? Please explain'; and 'Please explain why an ordinary Seismograph cannot record slow earthquakes.'). According to the Model of Domain Learning (Alexander, 2004; Dinsmore & Alexander, 2016), the recall question measured surface-level processing related to the basic encoding of textual content, and the open-ended questions measured deep-level processing related to a greater coordination of prior knowledge to interpret and make inferences from text. These different questions types were first scored individually and then summed. For writing one correct concept for each question, one point was awarded. Two independent raters rated the scores of the reading test and discussed the inconsistent scores to achieve consistency. The Cohen's Kappa for the whole reading test was .87. The revisions to the prior knowledge test and reading comprehension test were confirmed by two middle-school teachers who taught earth science and had master's degrees in science.

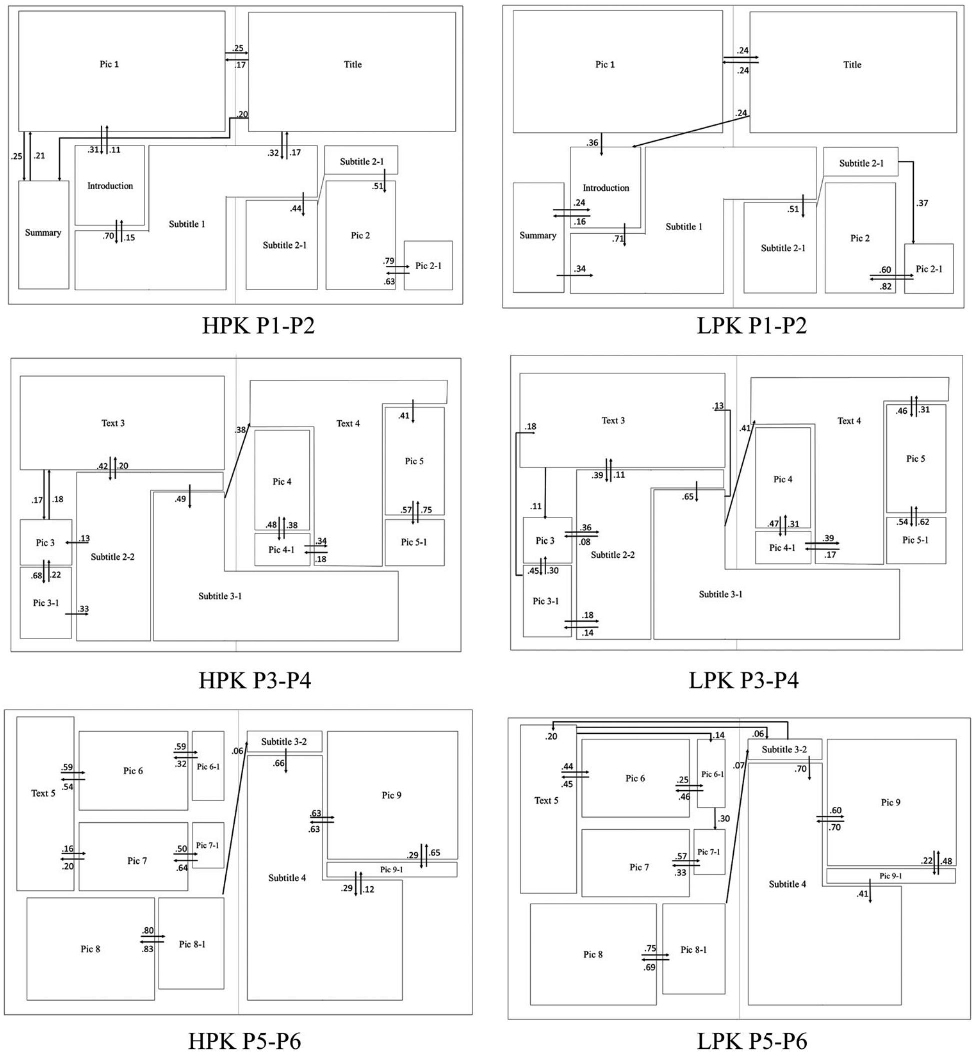


Figure 1. The learning material used from the magazine *Scientific American* (Liu, 2009). This figure indicates the results of sequential analyses of eye fixations for HPK and LPK groups. Black lines indicated AOIs; participants were not shown these lines. The percentages near the arrows indicate significant transition percentages from starting areas to subsequent areas.

Apparatus

Tobii Pro Glasses 2 recorded participants' eye fixations and movement patterns across the six-page science article. The video resolution was 1920*1080 pixels, the sampling rate was 100 Hz, the accuracy was 0.62°, and the precision in the Tobii Pro Glasses 2 was 0.05°. The eye tracker system was fixed to the participants' head using a bridle. A chin bar was used to increase the recording precision of eye fixations.

Procedure

The eye-movement study was a one-by-one experiment. Participants who provided informed consent completed the prior knowledge test and the questionnaire on epistemic beliefs in science. They then performed a real-world reading task. First, they wore Tobii Pro Glasses 2 for calibrating eye fixations, while seated in front of a desk with a bookshelf with a science magazine on it. The bookshelf was used to increase the recording accuracy of eye fixations because some readers would glimpse (instead of lowering their head to read) at the information on the bottom of the article, causing many eye fixations to be recorded loosely. In addition, we adjusted the light intensity to moderate instead of too dark (which may affect reading clarity) or too bright (which may cause reflected light to impede the data collection of eye fixations). Therefore, the gaze samples of all the participants were above 84%, indicating that relative complete data were collected without significant loss of eye fixation records. The measuring area of the reading material was 42×27 cm, the distance between the participants' eyes and the reading material was 35 cm near to real reading conditions. Therefore, the viewing angle of the reading material was 62×42 degrees. This viewing angle could record eye movement data for the Tobii Pro Glasses 2; the official manual indicates that the largest viewing angle for recording is 82×52 degrees both horizontally and vertically. Then, the participants were instructed to read and turn the magazine pages freely (only the six pages of the article). There was no time limit for reading the article. Finally, they completed the reading test without being provided with the original article and answered a questionnaire in which they could provide subjective ratings for article interestingness and difficulty. The experimental procedure lasted approximately 50–60 min.

Data analysis

Areas of interest

To understand readers' overall and detailed reading patterns, the areas of interests (AOIs) (see Figure 1) of the science article were divided into large (e.g. the whole article, texts and diagrams sections) and small units (e.g. specific paragraphs of subtitles in the texts and different types of diagrams and diagrams captions). The AOIs were named based on the article structure as follows: (1) title (named Title); (2) main body of the text, which consisted of an introduction and four paragraphs of the subtitles (named Introduction and Subtitles 1–4). Because some paragraphs of the subtitle crossed two pages, for example the second paragraph of the subtitle, they were named Subtitle 2-1 and 2-2; (3) supplementary information, which contained a point summary (named Summary), and three text sections on Pages 3, 4 and 5 (named Text 3, Text 4, and Text 5); (4) nine diagrams (named Pic 1 to Pic 9). Among the diagrams, pictures 1, 3, and 4 were decorative; pictures 2 and 5 were representational; pictures 6, 7, and 8 were statistical; and picture 9 was explanatory; and (5) diagram captions, which consisted of eight captions (named Pic 2-1 to 9-1). Picture 1 did not have a caption.

The AOIs of all text paragraphs, diagrams, and diagram captions were not overlapping (Please see Figure 1). In Figure 1, the smallest AOI was pic 7-1 with a 6.54×5.72 degrees viewing angle, and the largest AOI was pic 1 with a 32.65×19.46 degrees viewing angle.

Eye movement indicators

Several eye-movement indicators were used in this study based on previous text-and-diagram studies (Jian, 2016, 2018, 2019; Jian & Ko, 2017; Liao et al., 2020). They included the following: (1) total reading time, which refers to the time taken to finish reading from the start to end, reflecting the overall difficulty degree and cognitive effort required to process the reading materials; (2) total fixation duration, which refers to the sum of all fixation durations located in the AOI of the learning material, indicating readers' attention and cognitive investment; (3) proportion of total fixation durations, which is calculated as the fixation durations in specific AOIs (e.g. text, diagram) divided by the total fixation duration for the whole article, indicating readers' attention distribution to specific target regions of the learning material; and (4) number of saccades between text and diagrams, which refers to the total text-to-diagram saccades and diagram-to-diagram saccades, indicating readers' attempts to refer or/and integrate the information provided by the textual and pictorial representations.

To compare the reading sequences for both the HPK and LPK groups, a series of sequential analysis matrix calculations (Bakeman & Gottman, 1997; Jian & Ko, 2014, 2017; Tsai & Wu, 2021) were done to analyse the sequence of eye fixations across AOIs. For example, assume that an article was divided into four AOIs, there would be 4 (row) × 4 (column) matrix for the eye transition numbers of all the participants (e.g. from A-AOI to B-AOI, from A-AOI to C-AOI, A-AOI to D-AOI). If all participants had 100 numbers of eye transitions started from A-AOI (starting interest area), and 20 of them transferred to B-AOI (subsequent interest area), the transition percentage of A-AOI to B-AOI would be 0.2. Then, the expected value of the transition percentage would be calculated using the iterative proportional fitting procedure (IPFP) (Pukelsheim & Simeone, 2009). This procedure is a statistical calculation, that considers the sums of rows and columns in the matrix of eye transition numbers. The IPFP adjusts the rows and columns to obtain a closer approximation to the sums that exactly match the targets (observed value). This is followed by observed and expected values, and finally, the adjusted residual Z-score values are calculated to judge their significance. A Z-value greater than 1.96 indicated that the transfer sequence had reached the cutoff level of significance ($p < .05$).

Statistical analyses were performed using the SPSS (version 23); Hedge's *g* and the bias-corrected and accelerated (BCa) bootstrap confidence intervals were derived, on R (version 4.0.4), using the R libraries of 'car' (Fox & Weisberg, 2019) and 'boot' (Canty & Ripley, 2021; version 1.3-28) respectively. Adjustments were made to the *p*-values for multiple comparisons using Holm's correction.

Ethics caption

Informed consent was obtained from the participants through a consent form. The consent form described the details of the study, the way of pertaining data and anonymous process. Those who wished to participate indicated their consent by signing the form.

Results

Demographic measurements

Participants' prior knowledge and epistemic beliefs in science were measured as demographic data. To ensure that HPK and LPK participants indeed had distinguishing prior knowledge of earthquakes and typhoons relevant to the learning material in this study, a t-test was performed with prior knowledge groups as the independent variable and the prior knowledge test as the dependent variable. Table 1 shows that the participants were successfully selected for the two target groups and that the HPK group's test scores had more significance than those of the LPK group, $t(47) = 7.81$, $p < .001$, Hedge's $g = 2.20$; Levene's test, $F(1,47) = 1.74$, $p = .19$; 95% BCa CIs for HPK [6.83, 7.74] and LPK [4.77, 5.46]. For the questionnaire measuring the epistemic beliefs in science, no significant differences were found between the total scores of both groups, $t(47) = 1.10$, $p > .05$, Hedge's $g = 0.31$; Levene's test, $F(1,47) = .46$, $p = .50$; 95% BCa CIs for HPK [105.78, 111.26] and LPK [103.63, 109.197].

Reading comprehension test

To answer the first research question about the participants' understanding on different dimensions of reading comprehension, t-tests were conducted on total scores and the sub-scores on free-recall, main-idea, and comprehension question types, with Welch's t test conducted on the comparison of free-recall question scores due to violation of equal variance. The results are presented in Table 2. The results showed that for the free-recall question, $t(37.49) = 2.63$, adjusted $p = .04$, Hedge's $g = 0.76$; Levene's test: $F(1, 47) = 4.78$, $p = .03$; 95% BCa CIs for HPK [4.97, 6.95] and LPK [3.23, 4.69], reading comprehension questions, $t(47) = 2.32$, adjusted $p = .049$, Hedge's $g = .65$; Levene's test: $F(1, 47) = 1.61$, $p = .21$; 95% BCa CIs for HPK [4.17, 5.91] and LPK [3.12, 4.35], and the total score of the reading comprehension test $t(47) = 3.44$, adjusted $p = .005$, Hedge's $g = .97$; Levene's test: $F(1, 47) = 1.85$, $p = .18$; 95% BCa CIs for HPK [11.52, 14.78] and LPK [8.31, 10.96]; the HPK group outperformed the LPK group. However, both groups had no significant differences in the scores of the main-idea

Table 1. Means and standard deviations of demographic data for HPK and LPK readers.

	HPK		LPK	
Measures	*M*	*SD*	*M*	*SD*
Prior knowledge test	7.39	1.12	5.19	0.85
Epistemic beliefs in science	108.30	6.83	106.04	7.48

Table 2. Means and standard deviations of the reading test for HPK and LPK readers.

	HPK		LPK	
Measures	*M*	*SD*	*M*	*SD*
Free recall essay question	5.83	2.95	3.92	1.96
Main-idea essay question	2.35	0.83	1.85	0.93
Comprehension essay questions	5.09	2.23	3.81	1.60
Total scores	13.27	4.05	9.58	3.46

questions, $t(47) = 1.99$, adjusted $p = 0.052$, Hedge's $g = .56$; Levene's test: $F(1, 47) = .04$, $p = .84$; 95% BCa CIs for HPK [1.46, 2.15] and LPK [1.91, 2.61]. The p-values reported above were adjusted for having conducted a family of four comparisons.

Eye movement patterns

To answer the second research question about whether the eye movements of HPK and LPK readers are different, the results for overall eye movements for the whole article, detailed eye movements for specific text and diagram sections, and reading sequences are reported below.

Overall eye movements

To understand the overall article reading patterns of the HPK and LPK groups, the total reading time of the article; total fixation duration for text, diagrams, and diagram captions; proportion of total fixation durations for text, diagrams, and diagrams captions; and total number of saccades between relevant texts and diagrams and between irrelevant texts and diagrams were considered as dependent variables. The results of the t-tests are shown in Table 3.

Firstly, the HPK group appeared to spend longer total reading time for the entire article, although the difference was marginally significant after adjustment for multiple comparisons, $t(47) = 2.54$, $p = .057$, Hedge's $g = .72$, 95% BCa CIs for HPK [1152.90, 1695.33] and LPK [807.66, 1173.25]; Levene's test: $F(1, 47) = 1.55$, $p = .22$, and had more total fixation durations for the diagrams than the LPK group, with a significant mean difference shown by Welch's t test, due to violation of equal variance, $t(25.57) = 3.45$, $p = .01$, Hedge's $g = 1.02$; Levene's test: $F(1, 47) = 4.44$, $p = .04$; 95% BCa CIs for HPK [118.57, 223.22] and LPK [54.88, 81.17]. However, both groups showed no significant difference in the total fixation durations for the text section and for diagram captions, ps >. 05. Secondly, the HPK group had a significantly higher proportion of total fixation durations for diagrams than the LPK group, as revealed by Welch's test, $t(30.96) = 3.82$, $p = .004$, Hedge's $g = 1.12$; Levene's test, $F(1, 47) = 7.07$, $p = .01$; 95% BCa CIs for HPK [.12, .17] and LPK [.08, .10], but the LPK group had a significantly higher proportion of total fixation durations for the text section than the HPK group, $t(47) = -2.93$, $p = .025$, Hedge's $g = -0.83$; Levene's test: $F(1, 47) = .35$, $p = .56$; 95% BCa CIs for HPK [.71, .77] and LPK [.78, .82]. There were no significant differences

Table 3. Means and standard deviations of eye-movement indicators for HPK and LPK readers.

	HPK		LPK	
Measures	*M*	*SD*	*M*	*SD*
Total reading time of the article (minutes)	22.83	10.68	16.18	7.53
Total fixation duration of text section (seconds)	759.32	278.44	617.97	284.24
Total fixation duration of diagram section (seconds)	151.67	113.41	66.88	34.36
Total fixation duration of diagrams' captions (seconds)	131.86	74.16	92.45	65.10
Proportion of total fixation durations on text	0.74	0.08	0.80	0.06
Proportion of total fixation durations on diagrams	0.14	0.06	0.09	0.03
Proportion of total fixation durations on diagrams' captions	0.12	0.04	0.11	0.05
Total saccades numbers of relevant texts and diagrams	66.90	40.19	41.96	27.65
Total saccades numbers of irrelevant texts and diagrams	6.09	3.87	5.58	5.35

between the groups' proportion of total fixation durations for diagram captions ($p > .05$). The p-values reported above were adjusted for having conducted a family of seven comparisons. Thirdly, the HPK group had a significantly higher total number of saccades between relevant texts and diagrams than the LPK group, $t(47) = 2.55$, adjusted $p = .028$, Hedge's $g = .72$; Levene's test: $F(1, 47) = 1.18$, $p = .28$; 95% BCa CIs for HPK [4.70, 7.79] and LPK [3.90, 8.01], but there were no significant differences in the total number of saccades between irrelevant texts and diagrams ($p > .05$).

Detailed eye movements

To answer the third research question about understand the differences in detailed eye movements for the HPK and LPK groups, the total reading time of the six pages in the article and respective total fixations durations for paragraphs of subtitles in the text section, different types of diagrams, and different types of diagram captions were analysed. Multivariate analyses of variance were performed with prior knowledge (a between-subject variable) and different pages/ different paragraphs of subtitles in the text/ different types of diagrams/ different types of diagram captions (within-subject variables) as independent variables. Figures 2–6 show the results of each analysis.

Regarding the total reading time for the six pages, Figure 2 shows the main effects of prior knowledge ($F\ (1, 47) = 6.30$, $p < .05$, $\eta^2 = .12$) and different pages ($F\ (5, 235) = 29.56$, $p < .001$, $\eta^2 = .39$). An interaction effect was found between prior knowledge and different pages ($F\ (5, 235) = 3.49$, $p < .01$, $\eta^2 = .07$). The simple main effects showed that the HPK group spent significantly longer total reading time on Pages 3, 5 and 6 than on Pages 1, 2 and 4 (ps < .05), and the LPK group spent significantly longer total reading time on Pages 3 and 6 than on Pages 1, 2, 4, and 5 (ps < .05). Moreover, the HPK group spent significantly longer total reading time on Page 5 than did the LPK group ($t\ (47) = 3.21$, $p < .01$).

Because the content property (with several statistics diagrams) of Page 5 was more unique, a heat map (Figure 3) of this page is included to show the locations of the two groups' differences. The statistical values of the heat map was to sum up all the

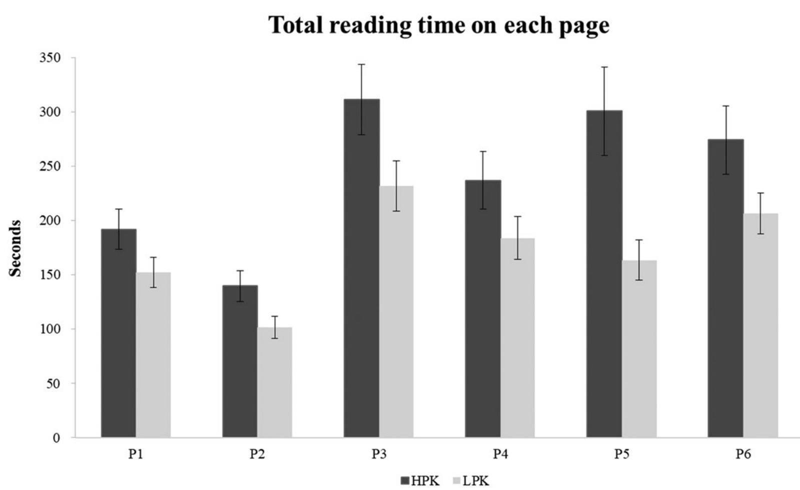
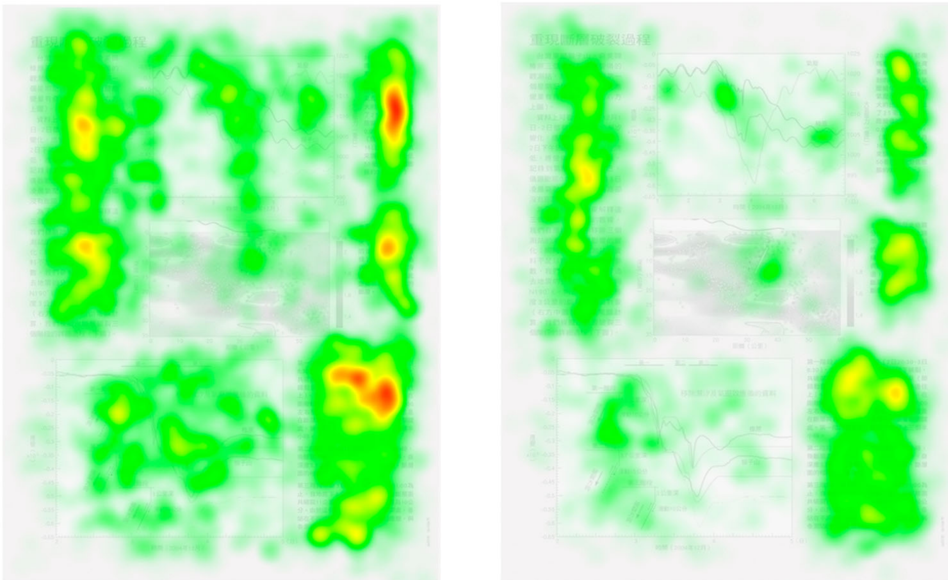


Figure 2. Total reading time (including the durations of fixations and saccades) for each page of the reading material for HPK and LPK readers.



(a) High prior knowledge group (b) Low prior knowledge group

Figure 3. Heat map of Page 5 consisting of text and several statistical diagrams for HPK and LPK readers. Opaque red colour indicates the areas on which readers spent the longest total fixation durations; transparent green colour indicated the areas on which readers spent the least total fixation durations.

fixation durations located on a specific area for all readers, and the average fixation durations of these readers were calculated and indicated in different colours. Longer and shorter average fixation duration on a specific area are indicated in red and green colours, respectively. Overall, the heat map showed that the HPK readers spent longer fixation durations on the statistics diagrams and their captions than did the LPK readers.

Regarding the total fixation durations on each character of the paragraphs (including Introduction and Subtitles 1–4) in the text section, Figure 3 shows a main effect of different paragraphs (F (4, 188) = 8.60, $p < .001$, $\eta^2 = .16$) but no main effect of prior knowledge or interaction effects between prior knowledge and paragraphs ($ps > .05$). A post-hoc analysis showed that participants overall spent significantly longer total fixation durations for each character of Subtitle 3 ('how typhoons produce slow earthquakes') and 4 ('the reason was pressure changes') than other paragraphs ($ps < .01$).

Analysis for specific diagram types and diagram captions

Regarding the total fixation durations for per square centimetre of diagrams, Figure 5 shows the main effects of prior knowledge (F (1, 47) = 10.57, $p < .01$, $\eta^2 = .18$) and diagram types (F (3, 141) = 20.81, $p < .001$, $\eta^2 = .31$); an interaction effect was found between prior knowledge and diagram types (F (3, 141) = 5.84, $p < .01$, $\eta^2 = .11$). The simple main effects showed that the HPK group spent significantly longer total fixation durations on representational diagrams and statistical diagrams than on decorative and explanatory ones ($ps < .05$). However, the LPK group spent significantly longer

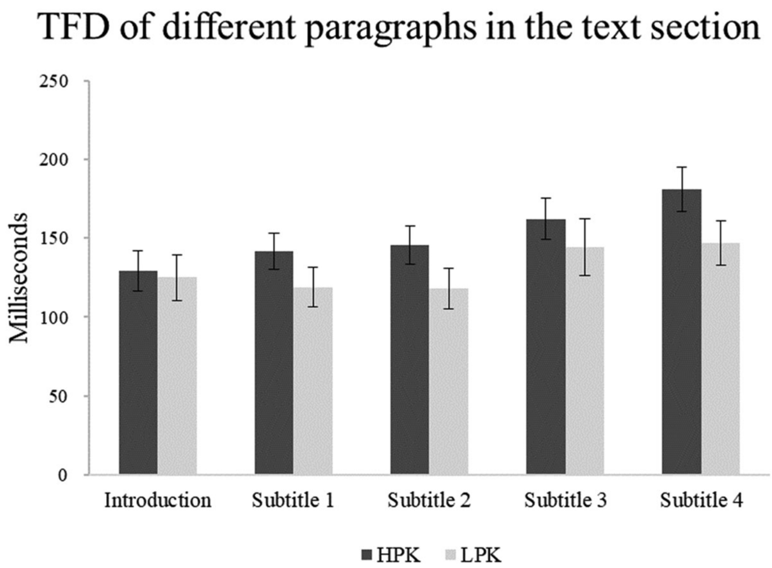


Figure 4. Total fixation durations of the paragraphs (each character) of each subtitle in the text section for HPK and LPK readers. The Introduction paragraph introduces typhoons and earthquakes as the two main natural disasters in Taiwan, Subtitle 1 paragraph describes dark energy in earthquake, Subtitle 2 paragraph introduces the slow earthquake discovered in Taiwan, Subtitle 3 paragraph introduces how typhoons produce slow earthquakes, and Subtitle 4 paragraph clarifies that the reason was pressure changes.

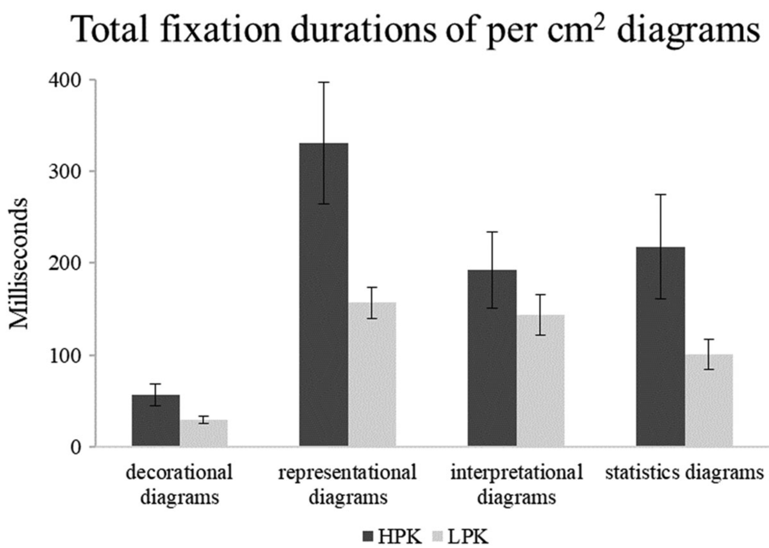


Figure 5. Total fixation durations of the different diagram (per cm^2) types for HPK and LPK readers.

total fixation durations on representational diagrams and explanatory diagrams than on decorative and statistical ones ($ps < .05$). Moreover, the HPK group spent significantly longer fixation durations on representational ($p < .05$) and statistical diagrams ($p < .001$) than did the LPK group.

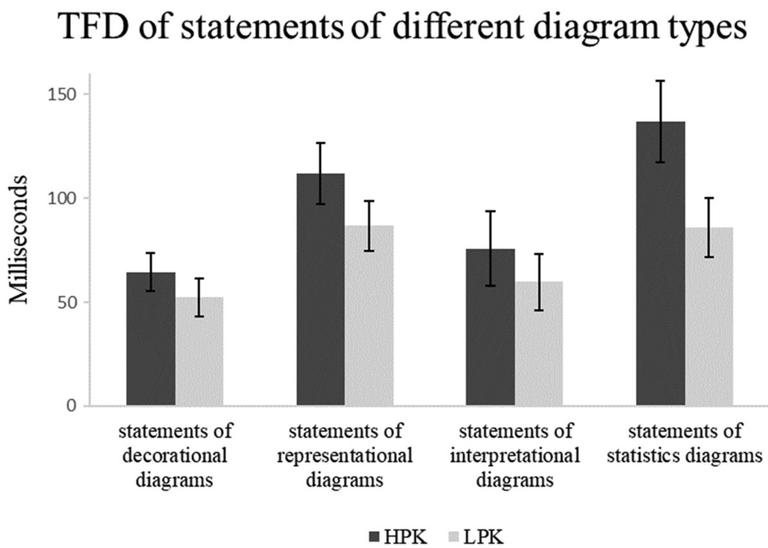


Figure 6. Total fixation durations of the captions (each character) for different diagram types for HPK and LPK readers.

Regarding the total fixation durations on each character of the diagram captions (four types), Figure 6 showed a main effect of diagram captions (F (3, 141) = 10.17, $p < .001$, $\eta^2 = .18$), no main effect of prior knowledge (F (1, 47) = 3.27, $p = .08$, $\eta^2 = .07$), and there was no interaction effect between prior knowledge and diagram captions ($p > .05$). A post-hoc analysis showed that the participants overall spent significantly longer total fixation durations on each character of statistical and representational diagram captions than on other diagram captions ($ps < .05$).

Analysis of eye-fixation sequences

To answer the fourth research question about examine readers' complete cognitive process and used reading strategies, a series of sequential analyses matrix calculations (Bakeman & Gottman, 1997; Jian, 2016; Jian & Ko, 2017) were performed to analyse the sequences of eye fixations for HPK and LPK groups. Because readers see two pages in one turning page, pages 1 and 2, pages 3 and 4, pages 5 and 6 were as analysis units individually. Each analysis unit contained several sections of paragraphs, diagrams, and diagram captions, each of which was divided as an AOI (see Figure 1), and the saccades made from each AOI to the other AOIs were calculated. The results of sequential analyses for both the groups are reported below.

Overall, there were a few similarities and differences in eye-fixation sequences between HPK and LPK groups. In terms of similarities, first, Figure 1 indicates that both groups tended to refer to each diagram and its diagram caption (e.g. Pic 2 to Pic 2-1, Pic 3 to Pic 3-1 … Pic 9 to Pic 9-1); the transfer probabilities for the eight pairs of diagrams and their captions were significantly higher than the expected values for the HPK (Z = 5.03–27.71, $ps < .001$) and LPK (Z = 6.21–18.6, $ps < .001$) groups. Second, although both groups performed references of semantic relevant of paragraphs and diagrams, this behaviour was more consistent for the HPK group than for the LPK group. For the HPK group, the transfer probabilities for the six paragraphs to their relevant diagrams (Introduction to Pic 1, Subtitle 2-1 to Pic 2, Text 4 to Pic 5, Text 5 to Pic 6, Pic 7, and Subtitle 4 to Pic 9) and four in reverse (including Pic 1 to Introduction, Pic 6 to Text 5, Pic 7 to Text 5, and Pic 9 to Subtitle 4) were significantly higher than the expected values ($Z = 1.96$–20.7, $ps < .05$). For the LPK group, the transfer probabilities for three paragraphs to their relevant diagrams (Text 4 to Pic 5, Text 5 to Pic 6, and Subtitle 4 to Pic 9) and four in reverse (Pic 1 to Introduction, Pic 5 to Text 4, Pic 6 to Text 5, and Pic 9 to Subtitle 4) were significantly higher than the expected values ($Z = 1.96$–16.94, $ps < .05$).

Regarding the differences between the two groups, first, Figure 1 indicates that the HPK group preferred to read the summary after reading the article title; the transfer probability of the article title to summary was significantly higher than the expected value ($Z = 3.25$, $p < .001$). The LPK group did not indicate this preference ($p > .05$). Second, during the beginning reading stage, the HPK group preferred to connect text content to the article title; their eye fixations were located on paragraph of subtitle 1 and regressed to the article title ($Z = 3.04$, $p < .01$). The LPK group did not exhibit this reading behaviour ($p > .05$). Third, the HPK group preferred text-and-diagrams references as mentioned earlier, but some LPK readers preferred text-and-diagram captions references. Examples include Subtitle 2-1 to Pic 2-1 ($Z = 2.98$, $p < .01$) and Text 5 to Pic 6-1 ($Z = 3.61$, $p < .01$). Four, the LPK group preferred to transfer their fixations from paragraphs to paragraphs than did the HPK group. Examples include Subtitle 3-1 to Text 3 ($Z = 3.16$, $p < .01$), Text 5 to Subtitle 3-2 ($Z = 2.02$, $p < .01$), and Subtitle 3-2 to Text 5 ($Z = 2.01$, $p < .01$).

Discussion

This study aimed to explore the reading comprehension and reading process of HPK versus LPK readers while reading a long scientific article in a (real) print reading situation using eye-tracking technology.

The results of this study indicated that the HPK readers remembered significant science knowledge and had better reading comprehension for the learning material than the LPK readers. This was consistent with the findings of the previous empirical research (Cromley et al., 2010; McCullough, 2013; Ozuru et al., 2007; Talwar et al., 2018) indicating that readers with high prior knowledge had better reading comprehension performance than those readers with low prior knowledge. In addition, the results of the reading test in this study also confirmed both general reading comprehension theories (e.g. CI model, Kintsch, 1988, 2005; Kintsch & Van Dijk, 1978) and text-and-diagram reading theories (e.g. Cognitive Theory of Multimedia Learning (CTML), Mayer, 2005; Integrated Model of Text and Picture Comprehension, Schnotz & Bannert, 2003; Schnotz, 2014); thus, proposing that prior knowledge plays a very important role in reading comprehension.

The results obtained from measuring the eye movements offered some interesting findings. First, consistent with the finding of Ho et al. (2014) the measurements showed that HPK readers spent longer fixation durations and made more regressions on the diagrams than LPK readers. This study found that HPK readers are more capable of using multiple representations and know the importance of scientific diagrams for reading comprehension. Second, the results revealed that HPK readers spent significantly longer fixation durations on representational and statistical diagrams and had a higher percentage of transitional fixations between text and diagrams than LPK readers. The heat map of eye movements (Figure 3) also showed that the HPK readers engaged in a deeper process while reading statistical diagrams' content. For example, they invested significantly more time and mental effort to view the changes to the lines in the statistical diagrams according to the x-axis (e.g. time, distance) and y-axis (e.g. morning and evening tides, atmospheric pressure), indicating the broken processes of a fault. This finding corresponded to the previous research indicating that prior knowledge is important for the interpretation of scientific graphic representations (Cook, 2006). On the contrary, the LPK group rarely spent time on viewing the statistical diagrams in the reading material. Second, LPK readers were much more text-driven; the total fixation durations on text was significantly higher for the LPK readers than for the HPK readers, and they also exhibited a tendency to read the diagram captions rather than the diagrams after reading the text. For example, after reading the words in Subtitle 2-1 ('the slow earthquake discovered in Taiwan'), 37% of LPK readers transferred their eye fixations to the caption of Pic 2-1, but most HPK readers (51%) directly transferred their eye fixations to Pic 2-1, which was relevant to the words in Subtitle 2-1. Third, mature readers in both groups would engage in self-regulating their reading strategy to slow down their reading speed for processing more important information. The study evidence indicated that both HPK and LPK readers spent longer fixation durations on processing the paragraphs under Subtitles 3 and 4 (which explains the cause–effect relationship between typhoons and earthquakes) in the reading material than the paragraphs under Subtitles 1 and 2 (which introduced some basic concepts about earthquakes).

Study contributions and implications

This study has several important contributions and implications. First, this study provided on-line processing data of eye movements, thereby clarifying the underlying mechanism for the CI model (Kintsch, 1988, 2005) by focusing on how readers' prior knowledge influenced reading comprehension. In the CI model, the highest level of reading comprehension is situation model; it relies on readers to integrate their prior knowledge and textual information. Second, a sequential analysis was adopted to depict how HPK and LPK readers comprehend a long scientific article with multiple representations. This study not only provided data about 'how long' readers fixate on the data, but also about 'where' they are looking at, thereby helping understand the dynamic process of reading. Third, unlike previous research, which displayed the reading materials on monitors to investigate the effect of prior knowledge on reading processes (Cook et al., 2008; Jian & Ko, 2014; Ho et al., 2014), this study overcame technical limitations and recorded readers' eye movements in a real print reading situation, thus, representing a higher ecology in the real reading situation. The results of this study also had an instructional implication for teachers: HPK and LPK readers had very different reading patterns for a scientific article with many pages and multiple representations. LPK readers had limited ability to use pictorial representations to learn scientific concepts; therefore, it is important to teach them how to decode scientific diagram information and to integrate textual descriptions for developing a better reading comprehension of the scientific article, especially for the representational diagrams and statistical diagrams that LPK readers were not good at processing as shown in this study.

Study limitations and further research directions

This study has some limitations and aspects worth investigating further in future research. First, this study had the small sample (24 subjects in the HPK group, and 25 subjects in the LPK group), and it may result a limitation to construct a model of understanding the relationships between prior knowledge, reading processes (reflected by eye movements data), and reading comprehension (reflected by reading test scores). Further research may recruit more subjects to construct a model of investigating this important question. Second, the words in the reading material were small, and AOIs could not be created to investigate the processes by which words are decoded and comprehended. For example, how readers decode scientific terminology in this science article was not investigated. Since comprehending scientific terminology is a difficulty that most students encounter in science reading, further research could modify the reading material to enlarge the words. This will help clarify whether readers use contextual information, refer to the relevant diagram, or decode the terminology using morphological knowledge upon encountering scientific terminology in science articles. Third, the diagrams in the reading material were not big enough to divide the diagrams into small AOIs. Future research could enlarge the diagrams and allow them to be analysed in specific parts; therefore, it may be possible to distinguish if HPK and LPK readers cognitively engage differently with different parts of the diagrams. Specifically speaking, it would be possible to determine if HPK readers spend much time viewing the specific parts of the diagrams which were directly relevant to the text information and if LPK readers spend their reading time on the parts of the diagrams which were irrelevant to the text information. In addition, the next step of this study will be to investigate if HPK and LPK readers have different eye movements while reading science articles in a print versus on a digital (e.g. monitor) medium.

Acknowledgements

I thank Miss Yi-Jye Wu for collecting the data and Dr. Leo Yuk Ting Cheung for statistical consultation.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was financially supported from the grant MOST 110-2636-H-003-003- and MOST 111-2636-H-003-003- under Young Scholar Fellowship Program by Ministry of Science and Technology in Taiwan, and the 'Institute for Research Excellence in Learning Sciences' and 'Higher Education Deep Cultivation Project' of National Taiwan Normal University (NTNU), sponsored by the Ministry of Education, Taiwan.

ORCID

Yu-Cin Jian http://orcid.org/0000-0002-2994-4529

References

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction*, *16*(3), 183–198. https://doi.org/10.1016/j.learninstruc.2006.03.001

Alexander, P. A. (2004). A model of domain learning: Reinterpreting expertise as a multidimensional, multistage process. In D. Y. Dai & R. J. Sternberg (Eds.), *Motivation, emotion, and cognition: Integrative perspectives on intellectual functioning and development* (pp. 273–298). Erlbaum.

Ariasi, N., Hyönä, J., Kaakinen, J. K., & Mason, L. (2017). An eye-movement analysis of the refutation effect in reading science text. *Journal of Computer Assisted Learning*, *33*(3), 202–221. https://doi.org/10.1111/jcal.12151

Bakeman, R., & Gottman, J. M. (1997). *Observing interaction: An introduction to sequential analysis* (2nd ed.). Cambridge University Press.

Canty, A., & Ripley, B. D. (2021). *boot: Bootstrap R (S-Plus) Functions*. R package version 1.3-28.

Chaffin, R., Morris, R. K., & Seely, R. E. (2001). Learning new word meanings from context: A study of eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*(1), 225–235. https://doi.org/10.1037/0278-7393.27.1.225

Chen, M. L., & Chen, C. H. (2020). Do readers adjust their lower- and higher-level language skills according to text structures? Evidence from eye movements in Chinese text reading. *Journal of Research in Reading*, *43*(2), 180–200. https://doi.org/10.1111/1467-9817.12297

Conley, A. M., Pintrich, P. R., Vekiri, I., & Harrison, D. (2004). Changes in epistemological beliefs in elementary science students. *Contemporary Educational Psychology*, *29*(2), 186–204. https://doi.org/10.1016/j.cedpsych.2004.01.004

Cook, M., Wiebe, E. N., & Carter, G. (2008). The influence of prior knowledge on viewing and interpreting graphics with macroscopic and molecular representations. *Science Education*, *92*(5), 848–867. https://doi.org/10.1002/sce.20262

Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education*, *90*(6), 1073–1091. https://doi.org/10.1002/sce.20164

Cromley, J. G., Snyder-Hogan, L. E., & Luciw-Dubas, U. A. (2010). Reading comprehension of scientific text: A domain-specific test of the direct and inferential mediation model of reading comprehension. *Journal of Educational Psychology*, *102*(3), 687–700. https://doi.org/10.1037/a0019452

Dinsmore, D. L., & Alexander, P. A. (2016). A multidimensional investigation of deep-level and surface-level processing. *The Journal of Experimental Education*, *84*(2), 213–244. https://doi.org/10.1080/00220973.2014.979126

Duke, N. K., Pressley, M., & Hilden, K. (2004). Difficulties with reading comprehension. In C. A. Stone, E. R. Silliman, B. J. Ehren, & K. Apel (Eds.), *Handbook of language and literacy development and disorder* (pp. 501–520). Guilford.

Eitel, A. (2016). How repeated studying and testing affects multimedia learning: Evidence for adaptation to task demands. *Learning and Instruction*, *41*, 70–84. https://doi.org/10.1016/j.learninstruc.2015.10.003

Foster, T. E., Ardoin, S. P., & Binder, K. S. (2018). Reliability and validity of eye movement measures of children's reading. *Reading Research Quarterly*, *53*(1), 71–89. https://doi.org/10.1002/rrq.182

Fox, J., & Weisberg, S. (2019). *An R companion to applied regression* (3rd ed.). Sage.

Guo, D., McTigue, E. M., Matthews, S. D., & Zimmer, W. (2020). The impact of visual displays on learning across the disciplines: A systematic review. *Educational Psychology Review*, https://doi.org/10.1007/s10648-020-09523-3

Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of Memory and Language*, *32*(6), 717–742. https://doi.org/10.1006/jmla.1993.1036
Ho, H. N. J., Tsai, M. J., Wang, C. Y., & Tsai, C. C. (2014). Prior knowledge and online inquiry-based science reading: Evidence from eye tracking. *International Journal of Science and Mathematics Education*, *12*(3), 525–554. https://doi.org/10.1007/s10763-013-9489-6
Jian, Y. C. (2016). Fourth graders' cognitive processes and learning strategies for reading illustrated biology texts: Eye movement measurements. *Reading Research Quarterly*, *51*(1), 93–109.
Jian, Y. C. (2018). Reading instructions influence cognitive processes of illustrated text reading not subject perception: An eye-tracking study. *Frontiers in Psychology*, *9*, 2263.
Jian, Y. C. (2019). Reading instructions facilitate signaling effect on science text for young readers: An eye-movement study. *International Journal of Science and Mathematics Education*, *17*, 503–522.
Jian, Y. C. (2020). Teaching fourth-grade students of different reading abilities to read biological illustrations and integrate to text information: An empirical experiment. *Research in Science Education*, *50*(6), 2269–2282.
Jian, Y. C., Chen, M. L., & Ko, H. W. (2013). Context effects in processing of Chinese academic words: An eye tracking investigation. *Reading Research Quarterly*, *48*(4), 403–413.
Jian, Y. C., & Ko, H. W. (2014). Investigating the effects of background knowledge on Chinese word processing during text reading: Evidence from eye movements. *Journal of Research in Reading*, *37*(1), 71–86.
Jian, Y. C, & Ko, H. W. (2017). Influences of text difficulty and reading ability on learning illustrated science texts for children: An eye movement study. *Computers and Education*, *113*, 263–279.
Juhasz, B. J., & Rayner, K. (2003). Investigating the effects of a set of intercorrelated variables on eye fixation duration in reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*(6), 1312–1318. https://doi.org/10.1037/0278-7393.29.6.1312
Kintsch, W. (1988). The role of knowledge in discourse comprehension: A construction-integration model. *Psychological Review*, *95*(2), 163–182. https://doi.org/10.1037/0033-295X.95.2.163
Kintsch, W. (2005). An overview of top-down and bottom-up effects in comprehension: The CI perspective. *Discourse Processes*, *39*(2), 125–128. https://doi.org/10.1080/0163853X.2005.9651676
Kintsch, W., & Van Dijk, T. A. (1978). Toward a model of text comprehension and production. *Psychological Review*, *85*(5), 363–394. https://doi.org/10.1037/0033-295X.85.5.363
Kohl, P. B., & Finkelstein, N. D. (2008). Patterns of multiple representation use by experts and novices during physics problem solving. *Physical Review Special Topics-Physics Education Research*, *4*, 010111-1–010111-13. https://doi.org/10.1103/PhysRevSTPER.4.010111
Liao, C.-N., Chang, K.-E., Huang, Y.-C., & Sung, Y.-T. (2020). Electronic storybook design, kindergartners' visual attention, and print awareness: An eye-tracking investigation. *Computers & Education*, *144*, 103703. https://doi.org/10.1016/j.compedu.2019.103703
Liu, C. C. (2009, October). Slow earthquakes triggered by typhoons (in Chinese). *Scientific American*, *92*, 10–115.
Mason, L., Tornatora, M. C., & Pluchino, P. (2013). Do fourth graders integrate text and picture in processing and learning from an illustrated science text? Evidence from eye-movement patterns. *Computers & Education*, *60*(1), 95–109. https://doi.org/10.1016/j.compedu.2012.07.011
Mayer, R. E. (2005). Cognitive theory of multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 31–48). Cambridge University Press.
McCullough, R. G. (2013). The relationship between reader response and prior knowledge on African American students' reading comprehension performance using multicultural literature. *Reading Psychology*, *34*(5), 397–435. https://doi.org/10.1080/02702711.2011.643531
McNamara, D. S., Kintsch, E., Songer, N. B., & Kintsch, W. (1996). Are good texts always better? Interactions of text coherence, background knowledge, and levels of understanding in learning from text. *Cognition and Instruction*, *14*(1), 1–43. https://doi.org/10.1207/s1532690xci1401_1
Miller, B. W. (2015). Using reading times and eye-movements to measure cognitive engagement. *Educational Psychologist*, *50*(1), 31–42. https://doi.org/10.1080/00461520.2015.1004068

Ozuru, Y., Best, R., Bell, C., Witherspoon, A., & McNamara, D. S. (2007). Influence of question format and text availability on the assessment of expository text comprehension. *Cognition and Instruction*, *25*(4), 399–438. https://doi.org/10.1080/07370000701632371

Pukelsheim, F., & Simeone, B. (2009). *On the iterative proportional fitting procedure: Structure of accumulation points and L1-error analysis*. Publishing Institution: Universität Augsburg.

Rau, M. A. (2018). Sequencing support for sense making and perceptual induction of connections among multiple visual representations. *Journal of Educational Psychology*, *110*(6), 811–833. https://doi.org/10.1037/edu0000229

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. https://doi.org/10.1037/0033-2909.124.3.372

Renkl, A., & Scheiter, K. (2017). Studying visual displays: How to instructionally support learning. *Educational Psychology Review*, *29*(3), 599–621. https://doi.org/10.1007/s10648-015-9340-4

Scheiter, K., & Eitel, A. (2015). Signals foster multimedia learning by supporting integration of highlighted text and diagram elements. *Learning and Instruction*, *36*, 11–26. https://doi.org/10.1016/j.learninstruc.2014.11.002

Schnotz, W. (2014). Integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 72–103). Cambridge University Press.

Schnotz, W., & Bannert, M. (2003). Construction and interference in learning from multiple representation. *Learning and Instruction*, *13*(2), 141–156. https://doi.org/10.1016/S0959-4752(02)00017-8

Schüler, A. (2017). Investigating gaze behavior during processing of inconsistent text-picture information: Evidence for text-picture integration. *Learning and Instruction*, *49*, 218–231. https://doi.org/10.1016/j.learninstruc.2017.03.001

Singer, L. M., & Alexander, P. A. (2017). Reading on paper and digitally: What the past decades of empirical research reveal. *Review of Educational Research*, *87*(6), 1007–1041. http://dx.doi.org/10.3102/0034654317722961

Talwar, A., Tighe, E. L., & Greenberg, D. (2018). Augmenting the simple view of reading for struggling adult readers: A unique role for background knowledge. *Scientific Studies of Reading*, *22*(5), 351–366. https://doi.org/10.1080/10888438.2018.1450410

Tarchi, C. (2010). Reading comprehension of informative texts in secondary school: A focus on direct and indirect effects of reader's prior knowledge. *Learning and Individual Differences*, *20*(5), 415–420. https://doi.org/10.1016/j.lindif.2010.04.002

Tsai, M. J., & Wu, A. H. (2021). Visual search patterns, information selection strategies, and information anxiety for online information problem solving. *Computers & Education*, *172*, 104234. https://doi.org/10.1016/j.compedu.2021.104236

Tsai, M. J., Wu, A. H., & Chen, Y. (2019). Static and dynamic seductive illustration effects on text-and-graphic learning processes, perceptions, and outcomes: Evidence from eye tracking. *Applied Cognitive Psychology*, *33*(1), 1–2. https://doi.org/10.1016/10.1002/acp.3514

Williams, R. S., & Morris, R. K. (2004). Eye movements, word familiarity, and vocabulary acquisition. *European Journal of Cognitive Psychology*, *16*(1/2), 312–339. https://doi.org/10.1080/09541440340000196

Wu, C.-J., Liu, C.-Y., Yang, C.-H., & Wu, C.-Y. (2021). Children's reading performances in illustrated science texts: Comprehension, eye movements, and interpretation of arrow symbols. *International Journal of Science Education*, *43*(1), 105–127. https://doi.org/10.1080/09500693.2020.1858515

Yang, F.-Y., Huang, R.-T., & Tsai, I. J. (2016). The effects of epistemic beliefs in science and gender difference on university students' science-text reading: An eye-tracking study. *International Journal of Science & Mathematics Education*, *14*(3), 473–498. https://doi.org/10.1007/s10763-014-9578-1