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Differentiated processing strategies for science reading among sixth-grade students: Exploration of eye movements using cluster analysis

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ABSTRACT

This study used eye-tracking technology to investigate the different types of reading strategies that sixth graders adopt to comprehend illustrated science articles, as well as the relationship between reading process and reading comprehension. The participants were 122 sixth-grade students whose eye movements were monitored during silent reading of a science article containing one representational diagram and one explanatory diagram. Cluster analysis was performed based on five eye movement indices: first-pass (initial processing)/look-back (late-stage processing) total fixation duration on texts and diagrams, and number of saccades between text and diagram. Results showed that sixth graders adopted four types of reading strategy to read science article: Initial-global-scan students (21%) reading the science text and examining the science diagram for the first time tend to quickly scan the material, then read it carefully, and engage in saccade behavior. Shallow-processing students (58%) spent little time on the text or diagram during their first-pass and second-pass reading, and they also seldom engage in saccade behavior. Words-dominated students (12%) spend a long time reading the text during the first-pass reading. Diagram-dominated students (9%) spent considerable time and effort on diagrams during the first-pass reading, and outperformed the other three groups in the reading comprehension test. Students who were proficient at using diagram information could distinguish the importance of various types of science diagrams; they also spent much mental effort on the explanatory diagram compared with the representational diagram. A multiple regression analysis indicated first-pass total fixation durations on the diagram predicted reading comprehension performance.

1. Introduction

Science articles are typically a juxtaposition of texts and diagrams. Scientific texts generally contain strings of scientific terminologies, dense information, and abstract semantics (Halliday & Martin, 1993; Nagy & Townsend, 2012). Scientific diagrams are mostly informative, and have different types, such as representational, explanatory, and organizational (Carney & Levin, 2002; Kress & van Leeuwen, 1996; Unsworth, 2001). For example, a cell structure diagram (representational) consists of several labels and illustrates spatial structures to represent an abstract description of a text. A scientific diagram (explanatory) is composed of numerous symbols, patterns, and names that convey particular semantic information of organism operation. A diagram (organizational)

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showing the series of steps involved in performing cardiopulmonary resuscitation.

The process of comprehending scientific texts and diagrams has been investigated from two perspectives: thinking aloud and eye tracker application. Thinking aloud requires readers to express their thoughts when reading a paper. Use of self-verbal reports to investigate text and diagram comprehension strategies (McTigue, 2009; Moore & Scevak, 1997) has generated numerous crucial conclusions. For example, Moore and Scevak (1997) reported that fifth-grade students focused on details when reading an article, whereas ninth-grade students focused on processing diagrams and associating textual and pictorial information. Another research paradigm uses eye-tracking technology to conduct a process-oriented study on text and diagram reading by recording the eye movements of readers and subsequently inferring their cognitive processes. Hyönä and Nurminen (2006) asserted that eye movements are a suitable basis for investigating the spontaneous use of reading strategies because readers inevitably move their eyes while reading. Furthermore, information on eye movement provides accurate records of time and space that can be used to elucidate the section of a paper being read, duration of fixation, time at which a gaze shifts, and direction of shift at a fixation point. Vigorous development in the use of an eye tracker to investigate cognitive learning of science article comprehension has been observed (Jian, 2017, 2019; Hegarty & Just, 1993; Huang & Chen, 2016; Sung, Wu, Chen, & Chang, 2015; Tsai, Wu, & Chen, 2019; Yang, Huang, & Tsai, 2016). These studies have emphasized the eye movements of adults when they are reading science articles over those of children (Jian, 2017; Jian & Ko, 2017; Hannus & Hyönä, 1999; Mason, Tornatora, & Pluchino, 2013; Tsai et al., 2019), particularly in school settings.

Individual difference of student is a topic of interest in education. The use of reading strategies is highly relevant to reading comprehension (Cain, Oakhill, Barnes, & Bryant, 2001). Thus, investigating how readers use reading strategies to read is critical in reading education. Although considerable research has employed cluster analysis to classify individual differences in strategies for reading plain texts among adult readers (Hyönä, Lorch, & Kaakinen, 2002; Hyönä & Nurminen, 2006; Mason et al., 2013), limited research has focused on young readers' individual differences in reading strategies while comprehending illustrated texts (Mason et al., 2013). The sixth grade is an important stage for reading to learn (Chall, 1983). In many education systems, sixth-grade students prepare to enter junior high school, a phase during which they would need to focus on subject reading (e.g., scientific reading). Therefore, this study selected sixth-grade students as research participants.

1.1. Multimedia learning theory

Mayer's (2009) cognitive theory of multimedia learning (CTML) is the predominant theory describing multimedia learning. CTML is based on the dual-channel assumption (Paivio, 1990), limited capacity of information processing assumption (Baddeley, 1986), and active processing assumption (Mayer, 2008). The dual-channel assumption proposes that textual and pictorial information is processed by two channels of the cognitive processing system in humans (Baddeley, 1986; Paivio, 1990). Limited capacity of information processing assumption proposes that individuals have limited capacity to process such information within a specified time frame (Baddeley, 1986). Therefore, individuals must first select information to process in their working memory; this occurs when an individual is attentive to a relevant text and diagram. Second, because reading constitutes the active processing of information (Mayer, 2008), individuals organize selected information by linking information within a text and constructing associations between components of a diagram to code representational information into internal representations. Finally, individuals combine the organized information with their prior knowledge to form a coherent mental representation in order to achieve the purpose of reading comprehension. This process involves stimulating long-term memory and transferring the stimulated memory into working memory. The aforementioned processes do not necessarily occur in a linear sequence or a reversal sequence. Readers must coordinate only actively and monitor themselves during the switching process to successfully comprehend a text.

This theory clearly states that the reading process of an illustrated reading material progresses from selecting pieces of information from the text and/or diagram, to organizing the information into larger chunks of mental representations, and finally to constructing a mental model to comprehend the concept. However, the fine-grained processes of dealing with different representations of text and diagram remain unclear. Moreover, as the reading abilities of young and teenage readers are developing, it is reasonable to assume that their reading processes do not completely match the ideal situation indicated in CTML (Mayer, 2009). For example, young readers with poor reading ability are not good at decoding diagram information or they may ignore diagrams in science articles (Jian, 2017, 2019; Hannus & Hyönä, 1999). In this case, the process of selecting diagram information described in CTML may not be apparent in these young readers. Therefore, this study sought to identify differentiated patterns of fine-grained reading processes in young readers who are reading illustrated texts, ultimately to refine multimedia theory.

1.2. Eye movement research on science article comprehension for children and Adolescents

Eye movement recordings are a method that collects process-oriented data (Rayner, 1998). The earliest study of the eye movements of children during the processing of scientific texts and diagrams was conducted by Hannus and Hyönä (1999), who investigated reading processes and strategies adopted by elementary school fourth-grade students with high and low abilities when reading science textbooks. The research results indicated that illustrations helped high-ability and low-ability children to remember textual details. However, the illustrations helped only high-ability children to comprehend biological principles. Based on the eye movement data of the students, although the difference in total reading duration between the groups was nonsignificant, the students spent different amounts of time on different segments of the text and illustrations, indicating a difference between their cognitive strategies. The high-ability students spent more time processing the information presented in the illustrations and text and exhibited frequent eye movement between illustrations and text; however, less transitions between text and illustration was observed among the low-ability students. This finding suggests that children require certain cognitive resources to compare and integrate illustrated textual information. Hannus and Hyönä (1999) found that although each text contained a substantial number of pictures, the high- and low-ability children spent approximately only 6% of their time studying illustrations, which was considerably less than that spent by adults, who spent approximately 20%–30% of their reading time on illustrations (Author et al., 2015; Schmidt-Weigand, Kohnert, & Glowalla, 2010).

I and my colleagues (Jian, 2017; Jian & Ko, 2017) have conducted a series of eye movement studies in recent years to investigate the cognitive processes of elementary school students when processing scientific text and diagrams. Jian and Ko (2017) adopted the eye-tracking technique to examine differences among fourth-grade students with high and low reading comprehension skills while they were processing difficult or easy scientific texts and diagrams. In that study, students were asked to read moderately difficult and difficult biology materials and answer test questions. The results indicated that the low-ability students spent considerably more time on the moderately difficult materials than on the difficult materials, whereas the high-ability students spent more time and expended more effort reading the difficult materials. The two groups of readers spent the same amount of time on illustrations and texts (approximately 15% and 85%, respectively); however, their reading movements differed significantly. The sequential analysis of eye movements revealed that when the high-ability students read a difficult text and did not understand at the first attempt, they generally reread the first paragraph of the text. By contrast, the low-ability students continued reading the subsequent paragraph, thereby following a linear reading movement irrespective of their understanding of the reading material. This finding suggested that skilled readers continuously monitor their level of understanding. If such readers do not understand the previous paragraph, they generally reread it to obtain relevant information and refer to said information when reading the next paragraph. Unskilled readers lack comprehension and monitoring ability. Based on all transition probabilities, if eye movements and fixation points are included in calculation, the most significant difference between the reading movements of the two groups of readers is as follows: high-ability students exhibit two-way reading movements transitioning between paragraphs and between the two diagrams, whereas low-ability students exhibit a linear reading movement. However, both groups seldom refer to illustrations when reading text, and the ability of fourth-grade students to integrate texts and illustrations during reading is underdeveloped.

Jian (2017) investigated sixth-grade students based on their postreading comprehension scores and examined the difference between their reading processes (eye movement patterns) and reading characteristics (reading comprehension skill, literacy, scientific terminology, reading self-efficacy, subjective perception of text difficulty, partiality for a scientific diagram, and self-assessed learning outcome). The results indicated that readers with good performance had better reading self-efficacy, were more attracted to the diagrams, and had higher self-evaluated learning levels than the readers with poor performance did. However, the standard comprehension test scores, scientific terminology, and subjective perception of text difficulty in both groups were not significantly different. Moreover, eye movement measurements indicated that students with satisfactory performance on the reading comprehension test spent more time reading texts and interpreting diagrams than did their counterparts, and they frequently transitioned between illustrations and text while reading. Students with satisfactory performance generally first view all diagrams after reading the title and then read the text. This reading pattern was not observed in the students with poor performance on the reading comprehension test.

To our knowledge, eye movement studies have used text-only materials and employed college students as research participants to classify different reading types (Hyönä et al., 2002; Hyönä & Nurminen, 2006; Mason et al., 2013). Only one study has targeted young readers reading illustrated text. Mason et al. (2013) conducted an empirical study on picture and text comprehension among elementary school students; they recorded 49 fourth-grade students reading a scientific text and then classified the students' eye movements. The eye movement indices for the cluster analysis included the following factors: duration of the first-pass total fixation on text, diagrams, and rereading the text; number of saccades between text and diagrams; and total fixation duration for reinspecting diagrams (the calculation and description of each indicator are provided in the subsequent section under *Data Selection and Analysis*). Mason et al. found that the fourth-grade students exhibited three processing strategies during the processing of scientific diagrams and text: high, intermediate, and low integrators. High integrators (47%) spent longer on first-pass fixation and reinspecting diagrams, and frequently shifted fixations on the illustration when rereading a text segment. Intermediate integrators (39%) exhibited a shorter fixation time on the illustration during the first encounter with it, viewed the picture after rereading a text segment, and exhibited a shorter fixation time on the text while reinspecting the picture. Low integrators (17%) fixated the illustration for the shortest time during the first inspection, made no refixations at all on the picture, and exhibited the shortest fixation time on the text. High integrators presented significantly superior performance in the immediate and delayed posttest than did low integrators. However, the previous knowledge and reading abilities of all three groups exhibited no significant differences.

1.3. The present study

The present study had three research purposes: (1) to determine the differentiated patterns of reading strategies adopted by sixth-grade students in elementary school to comprehend scientific texts and diagrams, (2) to clarify whether readers with different reading patterns had different processes toward different types of science diagrams (representational and explanatory), and (3) to examine correlations of various reading characteristics (reflected by eye movement measurements) with performance in reading comprehension.

This current study expanded on previous research (Mason et al., 2013) by adding different types of science diagrams, selecting participants with different ages, and including more indicators to analyze eye movement. Specifically, there were three differences between their research and the present study: a) Mason et al. (2013) used one representational diagram in the science text; this study used a representational diagram and an explanatory diagram contained in the reading material to investigate whether readers of different reading types had different processes for comprehending these diagrams; b) Mason et al. selected fourth-grade Italian students to read a science article in Italy; this study selected sixth-grade students who were native speakers of Chinese to read a science article in Chinese; and c) apart from the eye movement indicators also used in Mason et al., this study included the proportion of total fixation on text and diagram and mean fixation duration to demonstrate the fine-grained reading processes involved in reading illustrated texts for young readers, ultimately to refine multimedia theory.

2. Methods

2.1. Participants

Participants were native speakers of Chinese. Initially, eight sixth-grade classes at elementary schools in Taiwan were recruited to complete a standard reading comprehension screening test (Ko, 2006). According to the criteria of this test, students with a possible learning difficulty in reading comprehension were excluded. In total, 132 able students (62 male students and 70 female students with a mean age of 12.1 years) participated in the eye movement experiment with the consent of their parents. All of the participants had normal or corrected-to-normal vision.

2.2. Reading materials

To study the processes of "read to learn" adopted by readers, the reading materials must be those that have not been taught to students and easy to understand for them. Materials from the seventh grade curriculum were subsequently selected as the research materials. For this study, a scientific text combined with two diagrams (one was representational, and the other was explanatory) was prepared based on a section on gas exchange and respiratory function from a natural science and life science textbook published by Kang Hsuan Educational Publishing. The text contained 439 Chinese characters (including punctuation marks) and described the gas exchange on the skin of a small organism in water and the respiratory movement in the human body. The two diagrams were extracted from the textbook and an online source (www.phyworld.idv.tw), respectively. In eye movement studies on the processing of scientific texts and diagrams, generally, the text is placed on the left and the diagram is placed on the right (Jian, 2017, 2019; Mason et al., 2013; Scheiter & Eitel, 2015). The text was presented on a computer screen and did not have a drop-down function or a subsequent page.

The reading comprehension test was developed by the researcher and comprised 12 true-or-false questions pertaining to the text ($n = 5$), the diagrams ($n = 4$), and the combination of text and diagrams ($n = 3$). The readability, difficulty, and answer correctness of the text were evaluated and reviewed by three experts, namely a college teacher with expertise in the psychology of reading, a PhD candidate majoring in science education, and an elementary school natural science teacher with a Master's degree. These three experts evaluated the reading material as moderately difficult, which was consistent with the result (2.98; 3 = normal) of a five-point self-assessment performed by sixth-grade students at the request of my research (2017).

2.3. Apparatus

Eye movements were recorded using the Eyelink 1000 eye tracker system at a sampling rate of 1000 Hz. The head of each participant was supported by a chinrest to prevent movement. Right eye was tracked. The reading material was presented on a 24-in monitor with a resolution of 1920×1200 pixels. Each Chinese character in the text was set to 28×28 pixels; each of the two diagrams was set to 700×500 pixels. The participants were asked to place themselves at a distance of 65 cm from the monitor and their eyes were leveled horizontally and vertically at 46° and 30°, respectively.

2.4. Procedure

In the eye movement experiment, pupil calibration was performed to ensure accurate fixation (acceptable error $< 0.5°$). The participants were then asked to practice reading a text and subsequently complete a comprehension test to familiarize themselves with the experimental and testing procedure. Previous eye movement studies have involved a near-natural reading environment and no time limit (Jian, 2019; Jian, 2016; Eitel, 2016; Mason et al., 2013; Yang, 2017). In the present study, the participants were allowed to read the reading materials and complete the comprehension test at their favored speed. When the participants understood the experimental procedure, the experiment was conducted, including calibrating the students' eye movements, reading the instructions, reading the text, and completing the 12 true-or-false comprehension test questions randomly presented on the monitor. The entire experiment required approximately 30 min.

2.5. Data Selection and Analysis

Because of poor eye calibration, substantial changes in pupil position, and failed data transfer in 10 participants, 122 valid samples (57 male and 65 female students with a mean age of 12.2 years) were collected. Eye movement data were obtained using Data Viewer and underwent statistical analysis. The following eye movement indices were selected for analysis. Among these eye movement indicators, "fixation" is the moment in which the eye locates on a certain area of the learning material to encode information (Poole & Ball, 2005; Rayner, 1998).

Total duration refers to the time from a text being displayed on the computer screen to the participant clicking “end.” This index represents the total duration of the entire reading activity, including the time required for processing the text and diagrams and thinking or resting (i.e., fixation shifted away from the monitor).

Total fixation duration refers to the total duration of fixations on the areas of interest (AOIs, text, representational and explanatory diagrams used as AOIs in this study). This index represents cognitive efforts in processing the reading material (text or diagram). In general, a long fixation duration indicates the requirement of considerable effort and cognitive resources for information processing (Hannus & Hyönä, 1999; Hegarty & Just, 1993; Miller, 2015).

First-pass total fixation duration refers to the total duration of all fixations on the AOI during initial reading and before exiting it. This index represents the initial reading process, including the decoding of words or objects and the preliminary extraction of meaning from a text (Henderson, Weeks, & Hollingworth, 1999).

Second-pass total fixation duration (or look-back fixation time) refers to the total duration of all fixations on an AOI excluding the first-pass total fixation duration; that is, the duration of fixations leaving the AOI and then returning to reread it (for the second time, third time, and so on). This index reflects the later stage of the reading process, where readers read for a purpose and text reading involves a high level of cognitive processing involving aspects such as comprehension and integration (Mason et al., 2013).

Number of saccades between text and diagram refers to the total number of times when eye fixation shifts from the text to the picture and from the picture to the text. This index reflected the cognitive effort in attempting to combine text and pictures (Hannus & Hyönä, 1999; Hegarty & Just, 1993; Johnson & Mayer, 2012; Mason et al., 2013).

Number of fixations refers to the sum of all fixations in an AOI. This index represents the strength of information processing (Jian & Ko, 2017; Scheiter & Eitel, 2015).

Proportion of total fixation duration refers to the total fixation duration on the AOI as a percentage of the total fixation durations on the entire reading material. This index represents the allocation of attention (Jian & Ko, 2017; de Koning et al., 2010; Hannus & Hyönä, 1999; Rayner, 1998).

Mean fixation duration is calculated by dividing the total duration of fixation on an AOI by the number of fixations. This index represents the duration of text decoding or visual stimulation (Jian & Ko, 2017; Mason et al., 2013; Miller, 2015).

3. Results

The research results, including eye movement measurements, test scores, and analysis of eye movement and the comprehension test, are presented as follows to answer the research questions of the present study. The minimum time threshold was set at 100 ms, which is the criterion used in eye movement research (Jian & Ko, 2017; Andrews, Miller, & Rayner, 2004).

3.1. Analysis of eye movement

We conducted a cluster analysis of the participants' eye movement data to answer the first research question (i.e., the differentiated patterns of processing strategies adopted by sixth-grade students while reading illustrated science text). First, the reading material was divided into two AOIs of text and diagrams. Hierarchical cluster analysis was performed on the eye movement data of 122 valid samples using the Ward method. The following five eye movement indices were used in the cluster analysis: first- and second-pass total fixation durations for the text and diagrams and the number of saccades between the text and diagrams. In hierarchical cluster analysis, Ward's method and square Euclidean distance were used as the basis for grouping. The participants were divided into three, four, and five groups based on the dendrogram of the cluster analysis; the combined rescaled distance cluster was 10, 5, and 4, respectively. Because the cluster analysis used distance as its classification criterion, a shorter relative distance corresponds with higher similarity between clusters. The three clusters combined at a distance of 10. This excessively large distance likely caused differences between the within-group characteristics, thereby disregarding the principle of cluster analysis. Therefore, the present study categorized the participants into four or five groups. The distance cluster combined for four and five groups of participants was approximately the same; however, when the participants were divided into five groups, one of these groups contained only eight participants (6%), whose reading behavior was similar to that of another group comprising 18 participants. In particular, the total time spent by both groups on the pictures during the first-pass reading was approximately the same as the average time spent by all participants. Furthermore, the second-pass total fixation duration for the text and diagram areas and number of saccades between the text and diagram were higher than the mean. Moreover, the two groups slightly differed in terms of the first-pass total fixation duration on the text [the 8- and 18-participant groups were higher and lower than the mean of all participants, both with a standard deviation (SD) of 0.5]. Therefore, the participants were divided into four groups for subsequent comparison.

Because the eye movement indices had different units of measurement (time and frequency), the initial values were converted into standard Z scores (Fig. 1) to present the cluster analysis results on the same scale and facilitate a more intuitive description of differences in groups' reading patterns.

Fig. 1 indicated that the reading pattern of students in Group 1 (n = 26; 21%; named initial-global-scan group) first rapidly scanned the material before reading it carefully when engaging in the saccade behavior. The first-pass and second-pass total fixation durations on the text and diagrams for the initial-global-scan students were lower than the mean; however, the second-pass total fixation durations of the group on the text and diagram were all 1 SD higher than the mean. The initial-global-scan students exhibited the highest number of saccades (approximately one-fold higher) among all four groups. Group 2 (n = 71; 58%; named shallow-processing group) spent little time fixating on the text or diagrams during the first-pass and second-pass readings, and readers in this group seldom engaged in saccade behavior. The eye movement indices of the shallow-processing students were all lower than the

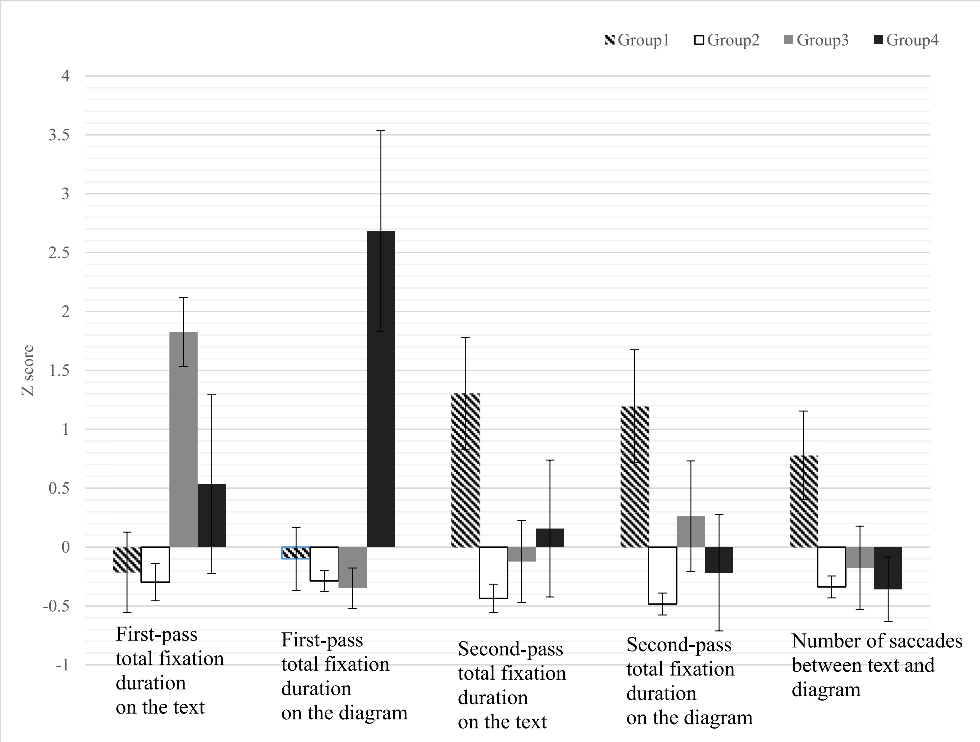

Fig. 1. Bar chart of eye movement z scores of the four groups of participants. (Note: Group 1 is the initial-global-scan group; Group 2 is the shallow-processing group; Group 3 is the words-dominated group; and Group 4 is the diagram-dominated group.)

mean, and the second-pass total fixation duration was shorter than half of the mean. Compared with the other groups, Group 3 (n = 14; 12%; named word-dominated group) spent a considerably longer total time on the first-pass reading of the text; that is, 2.67 times longer than initial-global-scan group and shallow-processing group. However, the first-pass total fixation duration of the word-dominated group on diagrams was the shortest among all four groups. The second-pass total fixation duration on the text and diagrams and the number of saccades for the word-dominated group approximated the mean of all participants. Group 4 (n = 11; 9%; named diagram-dominated group) exhibited the highest prominence, with a particularly long first-pass total fixation duration on the diagrams; that is, it spent 6–11 times longer than did the other three groups, which was 2.5 SDs higher than the mean. The first-pass total fixation duration on the text of the diagram-dominated group was slightly longer than the mean, indicating that this group spent the second longest time for reading. In addition, its second-pass total fixation duration on the text and diagrams and number of saccades approximated the overall mean.

To determine whether the eye movement indices of the four groups of participants exhibited a statistically significant difference, a one-way analysis of variance (ANOVA) was employed for between-group comparison. Table 1 shows the mean and SD of each eye movement index. The research results showed significant differences between the groups in the first-pass total fixation duration for the text ($F(3, 118) = 34.424$, $p < .001$, and $\eta^2 = 0.467$). The post hoc comparison of Scheffé indicated that the first-pass total

Table 1
Means and SDs of eye movement indices based on a cluster analysis for the four groups of participants.

Eye-movement indicators	Group 1 *N* = 26		Group 2 ***N* = 71**		Group 3 ***N* = 14**		Group 4 *N* = 11		Total ***N* = 122**		Post hoc
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	
First-pass total fixation duration											
Text (sec)	15.55	10.09	14.55	8.01	39.95	6.07	24.51	13.50	18.57	12.03	3 > 4, 1, 2; 4 > 2
Digram (sec)	3.07	3.78	1.99	2.16	1.64	1.69	18.93	7.25	3.71	5.80	4 > 1, 2, 3
Second-pass total fixation duration											
Text (sec)	150.74	65.48	53.69	28.32	71.11	33.48	86.74	48.26	79.35	56.19	1 > 4, 3, 2
Digram (sec)	35.21	20.61	6.04	6.82	18.97	14.14	10.65	12.78	14.15	16.95	1 > 3, 4, 2; 3 > 2
Number of saccades between text and diagram	13.96	7.48	4.99	3.16	6.29	4.94	4.82	3.28	7.03	5.84	1 > 3, 2, 4

Note. Group 1 is initial-global-scan group, Group 2 is shallow-processing group, Group 3 is words-dominated group, and Group 4 is diagram-dominated group.

fixation duration of word-dominated group was significantly longer than that of the other three groups ($p < .001$, $p < .001$, and $p < .01$). The duration of diagram-dominated group was significantly longer than that of shallow-processing group ($p < .05$). First-pass total fixation duration on the diagram differed significantly between groups ($F(3,118) = 89.220$, $p < .001$, $\eta^2 = 0.694$). The post hoc comparison revealed that diagram-dominated group had a significantly longer duration than did the other three groups ($p < .001$; $p < .001$; $p < .001$). Second-pass total fixation duration on the text significantly differed between groups ($F(3,118) = 35.345$, $p < .001$, $\eta^2 = 0.473$). Initial-global-scan group spent considerably more time than did the other three groups ($p < .001$, $p < .001$, and $p < .01$). Second-pass total fixation duration for the diagrams differed significantly between groups ($F(3,118) = 36.207$, $p < .001$, $\eta^2 = 0.479$). The post hoc comparison revealed that initial-global-scan group spent a significantly longer duration than did the other three groups ($p < .001$, $p < .01$, and $p < .001$), with word-dominated group spending a significantly longer time than shallow-processing group ($p < .01$). The number of saccades between text and diagram differed significantly between the groups ($F(3,118) = 25.105$, $p < .001$, and $\eta^2 = 0.390$). The post hoc comparison revealed that initial-global-scan group had a significantly higher number of saccades than did the other three groups ($p < .001$, $p < .001$, and $p < .001$). The five movement indices were significant in the test for homogeneity of variance, indicating that the assumption of homogeneity of variance was disregarded. Therefore, this study adopted Brown-Forsythe or Welch statistics to perform the robust test of equality of means. The post hoc comparison by Dunnett was conducted if significant between-group difference was observed. The results indicated that between-group difference was consistent with the ANOVA results.

Readers with personalized reading strategies might differ only in the sequence with which they process textual and pictorial representations. However, they allocate the same amount of time to texts and pictures throughout a reading activity. Therefore, this study examined whether the four groups of readers differed in the following eye movement indices, which are not separated by stages and are generally used in the literature: total fixation duration, number of fixations, proportion of total fixation duration, and mean fixation duration. Table 2 shows the means and *SD*s of each group.

According to the one-way ANOVA results, the groups exhibited significant differences regarding the total duration ($F(3,118) = 44.873$, $p < .001$, and $\eta^2 = 0.533$). The post hoc comparison revealed that the total duration for initial-global-scan group was significantly longer than those of the other three groups ($p < .001$, $p < .001$, and $p < .01$), and word-dominated and diagram-dominated groups spent significantly longer than shallow-processing group ($p < .05$; $p < .01$). The groups exhibited significant differences regarding the proportion of total fixation duration on the text ($F(3,118) = 2.879$, $p < .05$, and $\eta^2 = 0.068$); however, the post hoc comparison revealed no significant between-group differences (all $p > .05$). The groups exhibited significant differences for the proportion of total fixation duration on the diagrams ($F(3,118) = 6.151$, $p < .01$, and $\eta^2 = 0.135$). The post hoc comparison revealed that the proportions of initial-global-scan group and diagram-dominated group were significantly longer than that of shallow-processing group ($p < .05$ and $p < .05$). The groups exhibited significant differences for the total number of fixations on the text area ($F(3,118) = 26.642$, $p < .001$, and $\eta^2 = 0.404$). Initial-global-scan group exhibited a significantly higher number of fixations than did the other three groups ($p < .001$, $p < .001$, and $p < .05$). The groups exhibited significant differences regarding the number of fixations on the diagrams ($F(3,118) = 34.319$, $p < .001$, and $\eta^2 = 0.466$). The post hoc comparison indicated that initial-global-scan group fixated significantly more frequently on the diagrams than did shallow-processing group and word-dominated group ($p < .05$ and $p < .001$), and word-dominated group and diagram-dominated group fixated significantly more frequently than did shallow-processing group ($p < .01$ and $p < .001$). The groups exhibited nonsignificant differences regarding mean fixation duration of the text area ($F(3,118) = 2.163$, $p = .096$, and $\eta^2 = 0.052$). The groups also exhibited differences regarding mean fixation duration on the diagrams ($F(3,118) = 4.968$, $p < .01$, and $\eta^2 = 0.112$). The post hoc comparison revealed that the mean fixation duration for initial-global-scan group was significantly longer than those for shallow-processing group and word-dominated group ($p < .05$ and $p < .05$).

The homogeneity of variance test for the seven eye movement indices indicated that the total duration and number of fixations on the diagrams were significant, whereas the other indices were nonsignificant. Therefore, Brown-Forsythe or Welch statistics were

Table 2
Means and SDs of eye movement indices of the text and diagram areas for the four groups of participants.

Eye-movement indicators	Group 1 N = 26		Group 2 **N = 71**		Group 3 **N = 14**		Group 4 N = 11		Total **N = 122**		Post hoc
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	
Total duration of the article (sec)	257.77	88.94	104.41	44.85	160.90	48.70	172.89	55.86	149.75	84.18	1 > 4, 3 > 2
Proportion of total fixation duration											
Text (sec)	0.80	0.10	0.86	0.12	0.83	0.09	0.79	0.09	0.84	0.11	
Digram (sec)	0.18	0.09	0.10	0.11	0.16	0.08	0.20	0.09	0.13	0.11	4 > 2; 1 > 2
Number of fixations											
Text	608.31	196.26	297.13	143.90	372.00	98.21	430.09	149.02	384.02	195.60	1 > 4, 3, 2
Digram	131.50	67.69	33.59	29.91	84.93	49.92	101.09	49.98	66.43	60.25	1 > 3, 2; 3, 4 > 2
Mean fixation duration											
Text(ms)	285.53	47.26	261.98	41.82	269.41	30.60	262.28	29.26	267.88	41.66	
Digram(ms)	277.40	42.53	240.27	52.21	228.26	71.19	273.61	25.88	249.81	53.59	1 > 2, 3

Note. Group 1 is initial-global-scan group, Group 2 is shallow-processing group, Group 3 is words-dominated group, and Group 4 is diagram-dominated group.

adopted to test the total duration and number of fixations on the diagrams. The results reveled that these two indices differed significantly among the groups of participants. In particular, a post hoc comparison for total duration by Dunnett revealed a significantly longer duration for initial-global-scan group than for the other three groups ($p < .0010$, $p < .001$, and $p < .01$) and significantly longer durations for word-dominated group and diagram-dominated group than for shallow-processing group ($p < .01$ and $p < .05$). These results were consistent with the one-way ANOVA result, where the total durations for Groups of initial-global-scan, word-dominated, and diagram-dominated were significantly longer than that of shallow-processing group. A post hoc comparison of the total number of fixations on the diagrams by Dunnett revealed that Groups of initial-global-scan, word-dominated, and diagram-dominated exhibited significantly higher numbers of fixations than did shallow-processing group ($p < .001$, $p < .05$, and $p < .01$); this finding was consistent with the one-way ANOVA result.

3.2. Analysis of the representational and explanatory diagrams

This study used a mixed design ANOVA with two factors (i.e., reading groups [Groups 1–4, between subjects] and diagram types [representational or explanatory, within subjects]) to answer the second research question (i.e., whether readers with different reading patterns have different processes toward different types of science diagrams [representational and explanatory]). Eye movement indices included total fixation duration, number of fixations, first-pass total fixation duration, second-pass total fixation duration, proportion of total fixation duration, and mean fixation duration were used. Fig. 2 shows the results.

For the total fixation duration, reading group and diagram types had significant main effects (F (3, 118) = 42.170, $p < .001$, $\eta^2 = 0.517$; F (1, 118) = 18.208, $p < .001$, $\eta^2 = 0.134$). The interaction of reading groups and diagram types also reached significance (F (3, 118) = 5.500, $p < .01$, $\eta^2 = 0.123$). Results of the simple main effects of interaction showed that reading groups had a significant effect on viewing the representational (F (3, 236) = 23.70, $p < .001$, $\eta^2 = 0.232$) and explanatory diagrams (F (3, 236) = 54.76, $p < .001$, $\eta^2 = 0.410$). The three groups of initial-global-scan, word-dominated, and diagram-dominated groups had a significantly longer total fixation duration compared with the shallow-processing group on viewing the representational diagram ($p < .001$, $p < .01$, and $p < .001$, respectively) and the explanatory diagram ($p < .001$, $p < .05$, and $p < .001$, respectively). The initial-global-scan group also reported significantly longer total fixation durations on the explanatory diagram compared with the words-dominated group ($p < .001$). For the initial-global-scan group, diagram types had a simple main effect (F (1, 118) = 28.22, $p < .001$, $\eta^2 = 0.193$); they spent much total fixation durations on reading the explanatory diagram than the representative diagram ($p < .001$). However, for the other three groups, the simple main effects were all insignificant (ps $> .05$), and spent similar total fixation durations on both diagrams.

For number of fixations, reading group and diagram type had significant main effects F (3, 118) = 36.676, $p = .000$, $\eta^2 = 0.483$; F (1, 118) = 15.874, $p = .000$, $\eta^2 = 0.119$). The interaction of reading groups and diagram types also reached significance (F (3, 118) = 3.029, $p = .032$, $\eta^2 = 0.072$). Results of the simple main effects of interaction showed that reading groups had a significant effect on viewing the representational (F (3, 236) = 24.39, $p = .000$, $\eta^2 = 0.237$) and explanatory diagrams (F (3, 236) = 45.99, $p = .000$, $\eta^2 = 0.369$). The three groups of initial-global-scan, word-dominated, and diagram-dominated groups had a significantly higher number of fixations compared with the shallow-processing group on viewing the representational diagram ($p < .001$, $p < .01$, and $p < .001$, respectively) and explanatory diagram ($p < .001$, $p < .05$, and $p < .001$, respectively). The initial-global-scan group had a significantly higher number of fixations on the explanatory diagram compared with the words-dominated group ($p < .05$). For the initial-global-scan group, diagram types had a simple main effect (F (1, 118) = 28.22, $p < .001$, $\eta^2 = 0.193$); they had a significantly higher number of fixations on viewing the explanatory diagram than the representative diagram ($p < .001$). For the other three groups, the simple main effects were all insignificant (ps $> .05$).

For the first-pass total fixation duration, reading group and diagram type had significant main effects (F (3, 118) = 89.220, $p = .000$, $\eta^2 = 0.694$; F (1, 118) = 17.902, $p = .000$, $\eta^2 = 0.132$). The interaction of reading groups and diagram types also reached significance (F (3, 118) = 14.053, $p = .000$, $\eta^2 = 0.263$). Results of the simple main effects of interaction showed that reading groups had a significant effect on viewing the representational (F (3, 236) = 16.15, $p = .000$, $\eta^2 = 0.17$) and explanatory diagrams (F(3, 236) = 105.37, $p = .000$, $\eta^2 = 0.573$). The diagram-dominated group spent significantly longer first-pass total fixation durations compared with the other three groups on viewing the representational diagram ($p < .001$, $p < .001$, and $p < .001$, respectively) and explanatory diagram ($p < .001$, $p < .001$, and $p < .001$, respectively). For the diagram-dominated group, diagram types had a simple main effect (F (1, 118) = 45.15, $p = .000$, $\eta^2 = 0.277$); they spent a longer first-pass total fixation duration on reading the explanatory diagram than the representative diagram ($p < .001$). The other three groups had similar first-pass fixation durations on both diagrams (ps $> .05$).

For the second-pass fixation duration, reading group and diagram type had significant main effects (F (3, 118) = 36.207, $p = .000$, $\eta^2 = 0.479$; F (1, 118) = 4.343, $p = .039$, $\eta^2 = 0.036$). The interaction of reading groups and diagram types also reached significance (F(3, 118) = 7.261, $p = .000$, $\eta^2 = 0.156$). Results of the simple main effects of interaction showed that reading groups had significant effects on viewing the representational (F (3, 236) = 16.17, $p = .000$, $\eta^2 = 0.171$) and explanatory diagrams (F(3, 236) = 42.37, $p = .000$, $\eta^2 = 0.350$). For the representational diagram, the initial-global-scan group spent significantly longer second-pass fixation durations compared with the shallow-processing ($p < .001$) and diagram-dominated ($p < .05$) groups. The words-dominated group also spent significantly longer second-pass fixation durations compared with the shallow-processing group ($p < .05$). For the explanatory diagram, the initial-global-scan group spent significantly longer second-pass fixation durations compared with the other three groups ($p < .001$, $p < .01$, and $p < .001$, respectively), and the words-dominated group also spent significantly longer second-pass fixation durations compared with the shallow-processing group ($p < .05$). For the initial-global-scan group, diagram types had a simple main effect (F (1, 118) = 27.84, $p = .000$, $\eta^2 = 0.191$); they spent a longer second-pass total

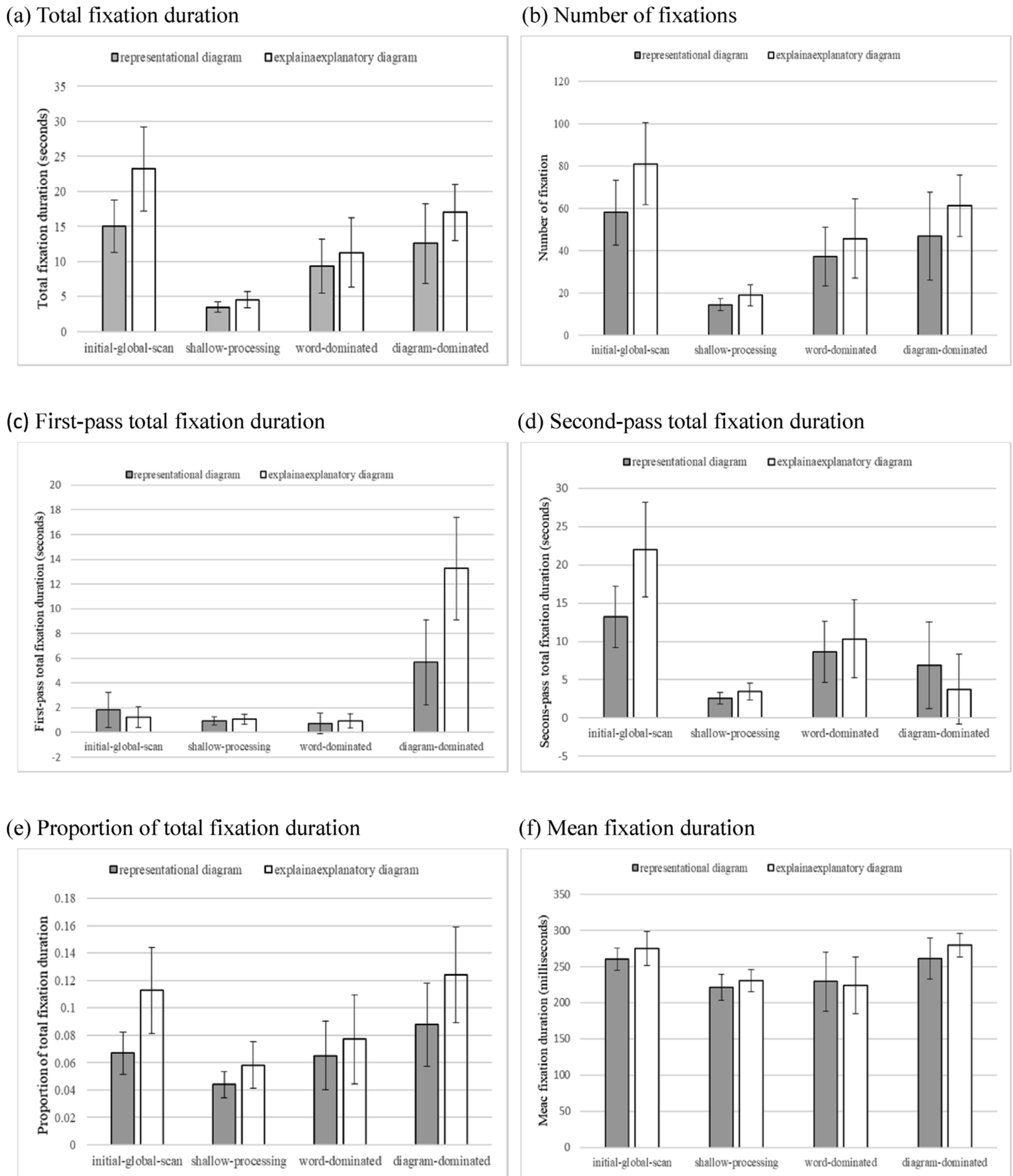

Fig. 2. Bar chart of eye movement indicators on viewing a representational and an explanatory diagram for the four groups.

fixation duration on viewing the explanatory diagram than the representative diagram ($p < .001$). The other three groups had similar second-pass fixation durations on both diagrams (ps $> .05$).

For the proportion of total fixation duration, reading group and diagram type had significant main effects (F (3, 118) = 6.795, $p = .000$, $\eta^2 = 0.147$; F (1, 118) = 15.382, $p = .000$, $\eta^2 = 0.11$). The interaction of reading groups and diagram types did not reach significant ($p > .05$). The proportion of total fixation duration in the explanatory diagram was significantly higher compared with the representational diagram. In the post hoc comparisons of the main effect of reading groups, the initial-global-scan ($p < .01$) and diagram-dominated ($p < .01$) groups showed a significantly higher proportion of total fixation duration on the diagrams compared

Table 3
Correlation analysis of eye movement indices and reading test score.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Total fixation duration of the article	–								
2. Total fixation duration on the text	0.86**	–							
3. Total fixation duration on the diagram	0.67**	0.53**	–						
4. First-pass total fixation duration on the text	0.14	0.19*	0.16	–					
5. First-pass total fixation duration on the diagram	0.11	0.10	0.25**	0.19*	–				
6. Second-pass total fixation duration on the text	0.93**	0.91**	0.52**	0.07	0.08	–			
7. Second-pass total fixation duration on the diagram	0.67**	0.50**	0.90**	0.07	−0.06	0.53**	–		
8. Number of saccades between text and diagram	0.38**	0.36**	0.54**	−0.07	−0.08	0.35**	0.54**	–	
9. Reading comprehension test score	0.10	0.03	0.17	0.01	0.30**	0.04	0.11	0.10	–

*$p < 0.05$ **$p < 0.01$.

with the shallow-processing group.

For the mean fixation duration, reading group had a significant main effect (F (3, 118) = 5.512, p = .001, η^2 = 0.123); the initial-global-scan group reported a significantly longer duration than the shallow-processing group in a post hoc comparison ($p > .05$). No main effect was observed on diagram type nor interaction of the reading group and diagram type ($ps > .05$).

3.3. Analysis of the reading comprehension test

For the reading comprehension test measuring the comprehension levels of the reading materials, results of the one-way ANOVA indicated that the reading test score exhibited significant between-group differences (F(3,118) = 5.650, $p < .01$, η^2 = 0.126). The post hoc comparison indicated that the score for the diagram-dominated group (M = 9.09, SD = 1.97) was significantly higher than that of the other three groups ($p < .05$, $p < .01$, and $p < .01$, respectively): initial-global-scan group (M = 7.04, SD = 2.07), shallow-processing group (M = 6.75, SD = 1.75), and words-dominated group (M = 6.57, SD = 1.40).

3.4. Combined analysis of eye movement and comprehension test data

Correlation analysis was performed on the eye movement indices and comprehension test scores to answer the third research question (i.e., correlations of various reading processes [reflected by the eye movement measurements] with performance in reading comprehension). Table 3 shows that the reading test score was significantly and positively correlated to the first-pass total fixation durations on the diagram (r = 0.30, p = .001). No statistically significant correlation ($ps > .05$) was observed between the reading test score and the other eye movement indicators: total fixation duration of the article/text/diagram, first-pass total fixation duration on the text, second-pass total fixation durations on the text/diagram, and number of saccades between text and diagram.

Multiple regression analysis was also used to clarify the relationship between reading process and reading comprehension performance. As the general indicator of total fixation durations on the article, text, and diagram did not significantly correlate to the reading test score, we excluded them in the succeeding multiple regression analysis. In the multiple regression analysis, the study took reading comprehension score as a dependent variable and the same five eye movement indices in the hierarchical cluster analysis as independent variables. The results are shown in Table 4. Only the first-pass total fixation durations on the diagram could predict reading comprehension performance (β = 0.336, $p < .001$). The other eye movement indices did not have statistically significant results ($ps > .05$) and could not predict the scores of reading comprehension performance.

4. Discussion

This study used eye-tracking technology to investigate the different types of reading strategies sixth-graders adopt to comprehend science texts and diagrams, as well as the relationship between reading process and reading comprehension. The results indicated

Table 4
The result of multiple regression analysis. (N = 122).

Eye movement indices	*B*	*SE*	*β*
First-pass total fixation duration on the text	.001	.001	-.054
Second-pass total fixation duration on the text	.001	.001	-.087
First-pass total fixation duration on the diagram	.001	.001	.336***
Second-pass total fixation duration on the diagram	.001	.001	.144
Number of saccades between text and diagram	.025	.034	.078
R^2	.12		
Adj R^2	.09		
F	3.24**		
df	(5116)		

that the reading patterns of the sixth-grade students could be classified into four types, one of which (Group 2, shallow processing; > 50%) involved a spending small amount of time on diagrams and seldom making integrative transitions. In this study, the group with most readers employed this shallow processing strategy, suggesting that they are not accustomed to using scientific texts and diagrams to help them understand a concept. Moreover, these students did not have the ability to combine texts and pictures during reading. This conclusion verifies the results of previous studies (Jian & Ko, 2017; Jian & Ko, 2017), which have examined eye movements of children during reading. The results accord with the results of eye movement studies that have adopted phonograms (Hannus & Hyönä, 1999) and the think-aloud approach (Moore & Scevak, 1997; Norman, 2012), and imply that visual literacy matures at a later stage of the developmental process (McTigue, 2009; McTigue & Flowers, 2011); this is a culturally universal phenomenon.

However, 30% of the readers (initial-global-scan and diagram-dominated) in this study generally used information conveyed in a diagram—a reading strategy similar to the one adopted by adults (Johnson & Mayer, 2012; Scheiter & Eitel, 2015). The only difference was that some readers immediately started to thoroughly process scientific diagrams during the first-pass reading process, whereas others generally re-examined these diagrams at a later stage. Table 2 indicates that 20% of readers (Group 1, initial-global-scan) generally first rapidly obtain an overview of diagrams and text and then read the text and thoroughly examine the diagrams when engaging in saccade behavior. For initial-global-scan readers, the total first-pass fixation durations for the text and diagrams were less than the means; however, their total second-pass fixation durations for the text and diagrams were both 1 SD higher than the means. Moreover, the initial-global-scan group exhibited the highest number of saccades (approximately one-fold higher than the mean) of all four groups. A quick scan of reading materials establishes a rough representation of the scientific knowledge to be learned and provides information on the spatial relation between the diagram and its components. Such preliminary understanding facilitates reading comprehension (Scheiter and Eitel, 2015; McCrudden, Magliano, & Schraw, 2011). In addition, approximately 10% of the sixth-grade students in this study (Type 4, diagram dominated) examined the diagrams in detail during the first-pass reading. The total first-pass fixation duration for the diagram dominated students was 2.5 SDs higher than the mean, indicating that they were aware that the diagram comprised crucial scientific concepts (Kress & van Leeuwen, 1996; Unsworth, 2001).

Moreover, we found that readers who were good at using diagram information could distinguish various diagrams but needed different processing times. The initial-global-scan group had a significantly longer total reading time, higher number of fixations, and longer second-pass total fixation duration on the explanatory diagram compared with the representational diagram. The diagram-dominated group also spent a significantly longer first-pass total fixation duration on viewing the explanatory diagram compared with the representational diagram. In contrast, shallow-processing and word-dominated students had no ability to distinguish the two functions of science diagrams, and spent similar processing times on both diagrams. Notably, the diagram-dominated students spent more than twice the processing time on the explanatory diagram than on the representational diagram while re-reading both diagrams. The explanatory diagram used in this study depicted not only the spatial structure of the human body but also the dynamic process of respiration using arrows to indicate that the ribs rise, diaphragm descends, and thoracic cavity enlarges when humans inhale. From the initial (first-pass) to the late processing (second-pass) stages of reading, the diagram-dominated students emphasized decoding the diagram information. They read the sentences describing the respiration to organize pieces of the textual information, and then carefully viewed the corresponding information in the diagram to connect the two representations and then integrate a mental model of understanding how human respiration operates. The findings of the eye movement pattern in this study depicted the fine-grained processes of CTML (Mayer, 2005), especially how skilled young readers organize and integrate multiple representations.

Regarding the relationship between cognitive processes and reading comprehension performance, the present results revealed that students who had better reading comprehension performance had longer first-pass fixation duration on the diagram, but not on the text. The multiple regression analysis also showed the same situation; only the indicator of first-pass fixation duration on the diagram could predict reading comprehension scores. First-pass fixation duration for the diagram includes global inspection and minute observation of diagrams during the initial reading processing stage. An explanation might be that the initial global inspection of diagrams provides a scaffolding of mental imagery to initiate the understanding of the scientific article (Scheiter & Eitel, 2015; McCrudden et al., 2011) and organizing pieces of the decoded diagrammatic information (Mayer, 2005) were important for comprehension of the illustrated text. Besides, on the question of why time spent reading the text did not relate to reading comprehension, a possible explanation is that readers had different standards of comprehension. Miller (2015) indicated that readers with a high standard of reading comprehension would slow down their reading to comprehend several concepts described in the text, whereas low-standard readers have no desire to understand the reading content, so they do not slow down their eye movements. From viewing the original eye movements' videos in this study and examining the answers of the reading test, we found that, despite efforts, some readers were unable to comprehend the concept described in the text. A few readers simply quit trying after the first attempt, whereas others were able to understand it after repeatedly reading the text material, and some understood quickly. Thus, four types of participants resulted in a trade-off between reading duration and comprehension performance; therefore, a statistical correlation between the two variables of reading time on text and the reading test score could not be identified. Another possibility was that the true-or-false questions in this study could not effectively reflect comprehension level. Detailed explanations are stated in the following section of limitations and future direction.

4.1. Limitations and future directions

The results of this study should be interpreted with careful consideration of several limitations. First, the reliability of the true/false questions may be low; the chance of guessing correctly was 50%. The raw data of this study indicated that 40% of the students accurately answered less than or equal to 50% of the questions, suggesting that some students might have guessed for some answers;

this was a research limitation of the present study. Future research could use multiple choice or open-ended questions to measure participants' reading comprehension skills. In addition, the reliability of answering questions should be confirmed in future research.

Second, the present study did not identify a statistical relationship between the number of saccades in the text and diagrams and reading comprehension performance, and this conclusion is inconsistent with those of previous studies where the two factors have exhibited positive correlations (Johnson & Mayer, 2012; Mason et al., 2013). Further investigation is required to determine whether this discrepancy is attributed to the text difficulty, different diagrams or information used, differences between young and old adults, or use of true-or-false questions in the comprehension test. The present study selected reading materials that have not appeared in student textbooks to eliminate the effect of prior knowledge; however, this effect could not be completely eliminated and could have influenced the reading process and reading comprehension performance. A safe approach for future studies to circumvent this problem is to include a prior knowledge test.

Third, the different findings of Mason et al. (2013) and this study need to be explained. Similar to Mason et al. (2013), the present study adopted cluster analysis to process data on the eye movements of readers reading an illustrated science text. Mason et al. (2013) recruited fourth-grade students whose native language was Italian, whereas the present study recruited sixth-grade students whose native language was Chinese. Mason et al. found that most of their participants were high integrators (47%). By contrast, our study identified a higher proportion of low integrators among the research participants. This difference may be attributed to the following three reasons. First, different reading materials were used; although both studies used scientific materials that fit on one screen, the reading material used by Mason was regarding the atmospheric pressure of air and included an illustration serving as proof of the existence of air. The science article used in the present study contained two types of diagrams: one was a representational diagram illustrating the gas exchange on the skin for small organisms in water, and the other was an explanatory diagram depicting the structures of the human body and the processes of respiration. This difference raises the questions of (a) whether readers rely on diagrams to understand a concept (i.e., the proof that air exists) given that physical materials contain abstract descriptions, and (b) whether sixth-grade students no longer rely on diagrams given that the concept to be understood (i.e., the respiratory system) is more complex than can be shown in diagrams and such students have prior knowledge of the human anatomy (e.g., the location of the thoracic cavity and ribs). Further empirical studies are required to answer these aforementioned questions. Second, Mason et al. and the present study might include different amounts of information in their diagrams. The diagram types used by Mason et al. (2013) and in the present study consisted of a considerable amount of information; they were not decorative diagrams. Indeed, representational and explanatory diagrams are informative (Carney & Levin, 2002). However, to our knowledge, no studies have defined the optimal amount of information to be included in a diagram. If the academic community establishes a standard form for informational diagrams in the future, a study can be designed to determine the effects of different types of diagrams (e.g., multiple versions of the same type of diagram containing different amounts of information or representational and explanatory diagrams containing the same amount of information) on the fixation duration of readers and number of saccades. Third, participants of different ages were recruited in Mason et al. and the present study. In Mason et al., most of the fourth-grade students were high integrators. Although older students (sixth-grade students) were included in the present study, these students seldom engaged in integrative transition. This phenomenon cannot be attributed to the notion that visual literacy matures at a later stage of the developmental process (McTigue, 2009; McTigue & Flowers, 2011).

4.2. Theoretical and educational implications

Regarding theoretical implication, this study found differentiated patterns of fine-grained reading processes while reading illustrated texts in young readers, thereby refining CTML (Mayer, 2005), and it is the first empirical study on eye movement to demonstrate that young readers with differentiated reading types had different processes on viewing science-related representational and explanatory diagrams. As CTML clearly states, multimedia learning material (e.g., combined words and picture) is processed as follows: selecting pieces of information in text and/or diagrams, organizing the information into larger chunks of mental representations, and constructing a mental model to comprehend the material. This study provided empirical evidence to expand the generalizability of CTML to some proportions of readers who are at the level of sixth-graders in elementary schools. Corresponding to the two important elements of CTML, namely, select and organize information, initial-global-scan students rapidly scanned the material and decided what information needed to be selected to process in the following deep reading, and then exhibited high-frequent transitions to organize the textual and pictorial information. Meanwhile, shallow-processing and words-dominated students did not select and organize diagram information at the initial processing reading stage. As shown in Table 1 and Fig. 2, both groups had significantly shorter first-pass total fixation durations on the diagram. Against our expectation, the words-dominated students began to decode diagram information at the late processing reading stage, based on their significantly longer second-pass fixation durations on the diagrams compared with the shallow-processing students; these durations were also higher than the mean of all of the participants. These findings indicate the diversity of reading processes adopted by young readers, and clarify the fine-grained processes of CTML (Mayer, 2005) for young readers with different reading strategies.

Regarding educational implications, the conclusion of this study provides teachers with insights on the differentiated reading processes adopted by sixth-grade students when reading scientific texts. In practice, teachers should identify their students' reading types and notice what they lack, and then develop teaching strategies to facilitate adaptive learning among students. For example, teachers could train students who seldom use pictorial information to interpret scientific diagrams. Students who lack integrative reading skills for text could be trained to understand semantic information from text. Based on the learning theory of CTML (Mayer, 2005), organizing textual and pictorial representations is crucial for good reading comprehension. Moreover, based on the present findings, first-pass total fixation durations on the diagram predict reading comprehension performance; thus, teachers can guide students to scan the diagram to decode the diagram information, such as symbols, names, object structures, and operations (Kress & van Leeuwen, 1996; Unsworth, 2001), before reading the article carefully.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compedu.2019.103652.

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