Read Writ (2017) 30:1447–1472
DOI 10.1007/s11145-017-9732-6

Eye-movement patterns and reader characteristics of students with good and poor performance when reading scientific text with diagrams

Yu-Cin Jian[1]

Abstract This study investigated the cognitive processes and reader characteristics of sixth graders who had good and poor performance when reading scientific text with diagrams. We first measured the reading ability and reading self-efficacy of sixth-grade participants, and then recorded their eye movements while they were reading an illustrated scientific text and scored their answers to content-related questions. Finally, the participants evaluated the difficulty of the article, the attractiveness of the content and diagram, and their learning performance. The participants were then classified into groups based on how many correct responses they gave to questions related to reading. The results showed that readers with good performance had better character recognition ability and reading self-efficacy, were more attracted to the diagrams, and had higher self-evaluated learning levels than the readers with poor performance did. Eye-movement data indicated that readers with good performance spent significantly more reading time on the whole article, the text section, and the diagram section than the readers with poor performance did. Interestingly, readers with good performance had significantly longer mean fixation duration on the diagrams than readers with poor performance did; further, readers with good performance made more saccades between the text and the diagrams. Additionally, sequential analysis of eye movements showed that readers with good performance preferred to observe the diagram rather than the text after reading the title, but this tendency was not present in readers with poor performance. In sum, using eye-tracking technology and several reading tests and questionnaires, we found that various cognitive aspects (reading strategy, diagram utilization) and affective aspects (reading self-efficacy, article likeness, diagram attraction, and self-evaluation of learning) affected sixth graders' reading performance in this study.

✉ Yu-Cin Jian
jianyucin@ntnu.edu.tw

[1] Department of Educational Psychology and Counseling, National Taiwan Normal University, No. 162, HePing East Road, Section 1, Taipei, Taiwan

Keywords Science reading · Cognitive process · Eye movements · Reader characteristics · Sequential analysis

Introduction

Primary school students often read illustrated texts in textbooks and in their daily lives, especially in the scientific domain. To successfully acquire knowledge while reading illustrated texts, the reader needs to decode, organize, and integrate the multiple representations of verbal and graphical information (Mayer, 2005; Schnotz & Bannert, 2003), which is a complicated cognitive activity; however, not all students are capable of learning successfully during reading.

Diagrams play an important role in scientific articles (Ainsworth, 1999; Cook, 2006; Ferk, Vrtacnik, Blejec, & Gril, 2003; Slough & McTigue, 2010). Diagram literacy means that the reader has the ability to decode and interpret the information that is presented in the diagram (McTigue & Flowers, 2011). McTigue and Flowers posited that children have poor diagram literacy because primary schools usually do not teach students how to either decode the information (e.g., the shapes and spatial positions of the components, the part-and-whole relationship, arrow meanings) that is presented in diagrams in scientific articles, or to use diagram reading strategies (e.g., referring to relevant information in text and diagram sections). In addition, young children have limited experience in reading scientific content, and diagram literacy is not necessarily improved if scientific knowledge is increased. Rather, it seems to be a cognitive behavior that develops slowly (Kress & van Leeuwen, 1996; Moore & Scevak, 1997).

Previous studies have used multiple methodologies to investigate text and diagram reading in young students. Each methodology elucidated a distinct feature of reading. Some studies used think-aloud protocols, in which the participants self-reported their thoughts as they were reading (Moore & Scevak, 1997; Norman, 2012). Others used outcome measures, in which the participants were asked to complete tests after reading scientific text with or without diagrams (McTigue, 2009; Rusted & Coltheart, 1979; Segers et al., 2008; Small, Lovett, & Scher, 1993). Recently, eye tracking has been used to investigate the cognitive processes of young readers while they read illustrated science texts. This method involves recording eye movements during reading to investigate individual cognitive processes (Hannus & Hyönä, 1999; Jian, 2016; Mason, Pluchino, Tornatora, & Ariasi, 2013a; Mason, Tornatora, & Pluchino, 2013b; Mason, Tornatora, & Pluchino, 2015). However, the findings obtained in these studies are inconsistent and still controversial. Several eye-tracking studies have reported that better learning performance is associated with greater integrative processing of textual and graphical information (i.e., readers made more saccades between text and diagram sections in articles). This phenomenon was observed in not only fourth graders (Hannus & Hyönä, 1999; Mason et al., 2013b), but also seventh (Mason et al., 2015) and eleventh graders (Mason et al., 2013a). However, Norman (2012) did not verify this positive correlation using the think-aloud protocol. We speculate that this might be due to the different methodologies used. Although the think-aloud protocol provides sufficient information about thinking while the participants are reading, it hampers the process of reading and makes it unnatural. Furthermore, this method only reflects conscious reading processes, and subconscious behavior is not measured. Therefore, these experiments might underestimate the usefulness of graphical information.

Methodologically, eye-tracking is a very useful technique for reading research. It can be used to measure these reading processes objectively and immediately (Rayner, 1998). In the past decade, eye-tracking research has been conducted to understand the process of reading in young readers, especially in relation to illustrated scientific text (Hannus & Hyönä, 1999; Jian, 2016; Mason et al., 2013a, b, 2015). Additionally, the analysis of eye-tracking has significantly progressed; the sequential analysis (Bakeman & Gottman, 1997) of eye movements can now reveal the dynamics of reading. By combining this with the fixation time data that previous eye-movement researchers (Hannus & Hyönä, 1999; Jian, 2016; Jian, Wu, & Su, 2014; Mason et al., 2015) have often used, we can now study the entire reading process.

Several studies have investigated the cognitive processes of young readers while they read illustrated text, and most of these studies have classified participants according to their reading ability (Harber, 1983; McTigue, 2009; Norman, 2012; Reid & Beveridge, 1986) or intelligence (Hannus & Hyönä, 1999). Until recently, few studies had examined groups formed according to the learning outcomes of participants (Mason et al., 2013b). If the purpose of reading is to learn, then learning outcomes after reading are crucial. These outcomes are determined by both cognitive (such as reading strategy, prior knowledge, number of characters known, and comprehension skill) and affective (reading self-efficacy, reading interest, reading engagement, self-evaluation of learning) factors. Learning outcomes are not necessarily restricted to the result of the readers' reading ability. Therefore, in this study, we investigated differences in young readers' cognitive and affective factors, and recorded the eye-movement patterns of those who performed well or badly on a reading task. Knowing how young students read illustrated text not only helps primary school teachers to understand their students in various reading-related situations, but also allows them to use appropriate instructions to help students to develop adequate reading strategies for the future.

Illustrated text reading in young readers

Reading of illustrated text has been investigated in recent years. Two famous theories have been used to explain the potential beneficial effects of multimedia materials: the cognitive theory of multimedia learning (Mayer, 2005) and the integrated model of text and diagram comprehension (Schnotz & Bannert, 2003). Both are based on the dual coding theory of Paivio (1990), which suggests that verbal and pictorial information are processed by different subsystems in the human brain to generate verbal and pictorial models; connecting these two models results in a better mental model compared to the use of a single textual model. This theory implies that readers who read text with diagrams will have better learning performance than those who read the same text without diagrams.

In previous studies, researchers used learning outcomes (McTigue, 2009; Rusted & Coltheart, 1979; Segers et al., 2008; Small et al., 1993) to investigate whether diagrams facilitate reading comprehension. The typical method was to use reading materials with or without diagrams, and researchers then compared the test scores of different groups. Although multimedia learning was found to be very effective in adults, its effect was variable in young readers. Several studies have indicated that students learn better when they read texts with diagrams (Rusted & Coltheart, 1979; Small et al., 1993), but others showed that multiple representations (scientific text and pictures) did not facilitate comprehension in young readers (McTigue, 2009; Segers et al., 2008).

Several studies have used think-aloud protocols, asking young readers to report their thoughts as they read. Moore and Scevak (1997) invited fifth-, seventh-, and ninth-grade students to read illustrated scientific texts, and verbally report their thoughts. Their results showed developmental differences in the reading strategies used to understand these articles. Ninth-grade students applied diverse reading strategies and were capable of using diagrammatic information that was relevant to the textual information. However, younger readers rarely used diagrammatic information, instead focusing on the detailed information presented in the text. Only 8% of fifth-grade students and 13% of seventh-grade students used the information shown in the diagrams. Using the think-aloud protocol, Norman (2012) asked second graders to read scientific texts with several illustrations (including photographs, realistic drawings, captions, labels, and diagrams). As the students read, they were instructed to think aloud about the text when they looked at the illustration information. Then, they completed a retelling and comprehension test. The findings showed that the number of times second graders used diagram-reading strategies was correlated with retelling measures, but not with reading comprehension performance.

Eye-movement research on multimedia learning for children

In the past decade, eye-tracking technology has been used extensively to investigate the cognitive processes of young readers reading illustrated scientific text. These studies have employed not only comprehension test measures but also eye movement data to investigate the relationship between learning outcomes and cognitive processes.

Hannus and Hyönä (1999) investigated how illustrations guide the attention of learners during text reading. They used eye-tracking technology to examine fourth-grade students who had good and poor abilities in relation to reading scientific textbook passages with several illustrations (including diagrams, tables, and photographs). The results showed that students with good abilities spent more time on reading the text, but this result was not statistically significant, because of the large amount of variance. However, students with good and poor reading abilities viewed the illustrations for a similar period of time. Surprisingly, only 6% of both groups' total reading time was spent on viewing the illustrations. To analyze the transfer between the text and illustration, the authors created a five-point scale (5 = very often to 1 = never) for two raters to assess whether the participants looked back and forth between the illustration and text sections. The results showed that students with good reading abilities looked back and forth more often than students with poor reading abilities did. However, these scores were relatively low for both groups: average ratings were 2.6 and 2.0 for students with good and poor abilities, respectively. Additionally, Hannus and Hyönä did not find a significant correlation between students' comprehension, based on questions about the illustrations, and the amount of time spent inspecting the illustrations. However, a significant positive correlation was revealed between successfully answering illustration-related questions and the amount of time spent reading the text section in the scientific article. These findings imply that the young readers engaged in text-driven reading, and did not pay much attention to the illustrations.

In recent years, Mason et al. (2013a, b, 2015) have carried out a series of pioneering experiments using eye movement tracking to examine how young students read illustrated text. A common characteristic of these studies is the use of cluster analysis of the eye movements of the participants to examine reading patterns in young readers, and to understand the association between cognitive processes (measured by eye movement tracking) and learning outcomes (measured by reading tests). For example, Mason et al. (2013a, b) recruited fourth graders to read an illustrated scientific text while their eye movements were recorded. Cluster analysis of eye movements was used to classify the participants into low, intermediate, and high integrators of text and diagram. These authors found that higher integrative processing of the illustrated text was associated with better learning performance. Additionally, 47% of the participants were classified into the high integrator group, whereas only 14% were low integrators. These data imply that most fourth graders have the ability to use the information presented in diagrams because the participants tried to connect this with the information in the text, although it is unclear if they integrated both semantic representations successfully. However, the previous studies (Hannus & Hyönä, 1999; Jian, 2016) reported that most fourth graders did not check the relevant text and diagram in parallel when reading illustrated scientific texts.

Mason et al. (2015), in an extended study, recruited seventh graders to read an illustrated scientific article while their eye movements were recorded. They performed cluster analysis and a series of hierarchical regression analyses to reveal which eye movement indicator might predict learning outcomes most effectively. The results indicated that only the patterns of integrative processing of text and diagram (calculated as the number of saccades between text and diagram) during second-pass reading (a less automatic and more targeted process) predicted learning outcomes, after controlling for individual differences in background knowledge, reading comprehension ability, and self-concept, regardless of whether the tests measured factual recall or the transfer of knowledge.

Reading is a dynamic, rather than static, process; therefore, sequential analysis is an ideal method to investigate the process of reading. Sequential analysis has usually been used in the past by psychologists to reveal interactions between people or to analyze moment-to-moment behavior (Bakeman & Gottman, 1997). A few recent studies have also used this analysis to investigate the reading strategies of adults (Jian et al., 2014), adolescent readers (Cook, Carter, & Wiebe, 2008a, b), and young readers (Jian, 2016). Jian investigated the reading strategies of young and adult readers when reading illustrated text. The researcher asked fourth-grade students with good reading abilities and undergraduate students to read a biological article with two diagrams, which was aimed at elementary school-level readers, from a scientific textbook. Eye movements in the sequential analysis showed that adult readers demonstrated bidirectional reading pathways for both text and diagrams, whereas children's eye fixations only went back and forth within paragraphs in the text and between the diagrams, and that the latter group made fewer references to both the text and diagrams. This finding suggests that although the fourth-grade children had good reading abilities, their visual literacy is not advanced enough to connect corresponding features among different representations, which is crucial in reading comprehension.

Affective factors in reading performance

From the perspective of motivation theory, several affective factors (e.g., reading self-efficacy, reading interest, reading engagement, self-evaluation of learning) may also influence reading performance.

Self-efficacy entails an individual's belief in his or her capacity to perform at a desired level (Bandura & Cervone, 1983), and may influence the individual's choice of what to do and how much effort to expend on a given activity (Schunk, 1981). Research has also indicated that learners' self-efficacy is positively related to reading comprehension (Katzir, Lesaux, & Kim, 2009). As for *reading interest*, research on its relationship with reading ability remains inconclusive. A positive correlation between the two has been reported (Baker & Wigfield, 1999; Taboada, Tonks, Wigfield, & Guthrie, 2009), but some researchers have reported only a weak correlation in the early elementary years (Kirby, Ball, Geier, Parrila, & Wade-Woolley, 2011). *Reading engagement* relates to the extent to which a person engages in a reading activity, such as encoding a series of words or showing reading comprehension, as well as reading strategies applied. Cognitive dimensions of a reading engagement index involve working hard to read and thinking deeply about the content (Unrau & Quirk, 2014; Wigfield et al., 2008). Reading engagement has been shown to have an impact on reading and learning outcomes (Guthrie & Wigfield, 2000). Finally, *self-evaluation of learning* entails an internal comparison between an individual's personal standards and his or her performance (Bandura & Cervone, 1983). To the best of my knowledge, the relationship between self-evaluation and reading has not been investigated so far.

The present study

The theory of multimedia learning (Mayer, 2005) clearly elaborates the cognitive processes of illustrated text reading. Successful reading comprehension requires the reader to decode, organize, and integrate multiple representations of verbal and pictorial information during reading. However, reader characteristics and affective factors are not mentioned in this theory, despite their possibility of being influential variables in multimedia learning. To further extend and contribute to the theory on multimedia learning, this study used eye-tracking technology in combination with sequential analysis, as well as reading tests and questionnaires, to investigate the cognitive processes and reader characteristics of sixth graders with good or poor performance when reading an illustrated scientific text.

From a practical perspective, although the relationship of reading comprehension and integrative processing behavior of textual and graphical information is positive for adult readers, the relationship is unstable and remains controversial for young readers. Some research has shown support for a positive relationship (Hannus & Hyönä, 1999; Mason et al., 2013b), but other studies have not (McTigue, 2009; Norman, 2012). A possible answer to this controversial issue was another important reason motivating the design of this study.

To investigate the cognitive processes of illustrated text reading among young readers who differed in terms of reading performance, several eye-movement indicators were selected based on previous studies that investigated the reading of diagrams or illustrated texts; each indicator reflects different types of cognitive processes (Grant & Spivey, 2003; Hannus & Hyönä, 1999; Hegarty, 1992; Jian, 2016; Johnson & Mayer, 2012). First, total reading time (the sum of all fixation durations on an area of interest [AOI]) indicates the degree of cognitive effort necessary for processing the information. According to dual-processing theories of cognition (Evans, 2007), deep processing requires a large amount of mental resources. In addition, readers have more cognitive demands when interpreting diagrams during science text reading (Cromley, Snyder-Hogan, & Luciw-Dubas, 2010). Therefore, we hypothesized that readers with good reading comprehension would spend longer on the reading material, not only for the text section but also for the diagram section. Second, the proportion of fixation durations (the fixation duration on a specific AOI divided by the total fixation duration during the learning episode) was measured, which reflects the selective attentional focus on specific target regions during learning. According to previous empirical research (Hannus & Hyönä, 1999; Jian, 2016), young readers of both high- and low-ability spent a substantial proportion of fixation durations on text sections rather than on diagram sections in illustrated texts. Therefore, we hypothesized both groups, with high- and low-reading performance, would showed similar patterns of fixation proportions as found in previous research. Third, the mean fixation duration (average duration of all fixations on an AOI) was calculated, which reflects the amount of time readers need to decode a certain stimulus, such as words or diagrams. Young readers usually have poor diagram literacy (McTigue & Flowers, 2011). When reading material is difficult, readers with good comprehension need to strategically adjust the allocation of their cognitive resources to achieve diagram comprehension, and thus slow down their eye movements to give themselves time to complete this process (Miller, 2015). Therefore, we hypothesized that readers with good reading comprehension would show longer mean fixation duration on the diagrams than those with poor reading performance. Fourth, the number of saccades from the text to the diagram (the number of times the participant changed their eye fixation from the text to the illustration) was examined, which reflects the inference and integration of textual and pictorial information. Based on the cognitive theory of multimedia learning (Mayer, 2005) and the integrated model of text and diagram comprehension (Schnotz & Bannert, 2003), connecting relevant information in the text and picture is essential for constructing a good mental model of illustrated text reading. Therefore, we hypothesized that readers with good reading comprehension would show more transition behavior, looking between the text and diagrams, than would those with poor reading performance.

To investigate the characteristics of young readers who differed in reading performance, several reading tests and questionnaires were used in this study. As mentioned in the literature review above, learners' self-efficacy has been found to be positively related to reading comprehension (Katzir et al., 2009). We hypothesized that readers with good reading comprehension would have better reading self-efficacy than those with poor reading performance. As for reading interest, research on its relationship with reading ability remains inconclusive (Baker & Wigfield, 1999; Kirby et al., 2011; Taboada et al., 2009), and to our knowledge, the relationship between self-evaluation and reading has not been investigated thus far. Therefore, we had no specific hypotheses regarding the degrees of article (and diagram) likeness and self-evaluation of learning of the good and poor readers in this study.

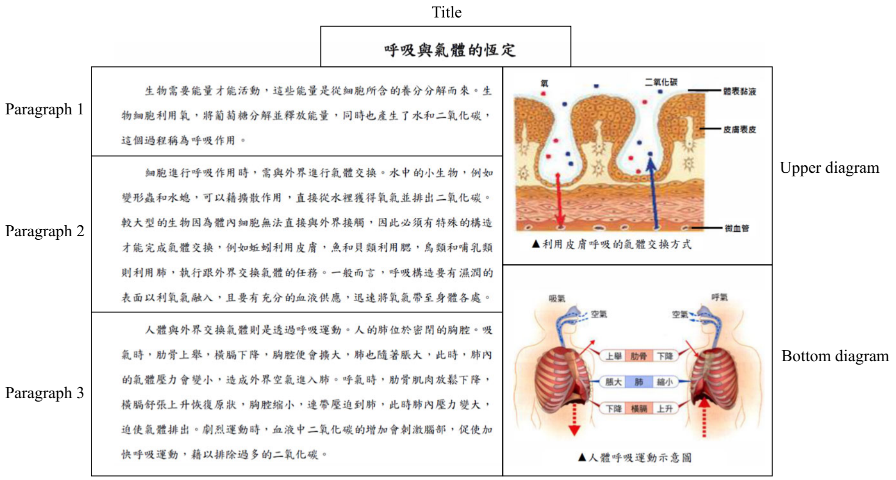
Method

Participants

Forty-two students (22 girls and 20 boys) in grade 6 from an elementary school in Taiwan participated in the experiment. Parental consent was sought and students were rewarded for their participation with stationery. The average age of the students was 12.3 years (range 11.7–12.9 years; *SD* = 3.2 months). None of the participants had difficulties with character recognition, according to their scores on the standard Chinese character recognition test (Huang, 2001), which evaluates the number of characters known. On this test, students write 200 Chinese characters in pinyin. The participants' average number of Chinese characters known met the 8.1 grade norm for character recognition (range 5.1–10.0 grade level; *SD* = 1.65 grade level). All participants had normal or corrected-to-normal vision.

Materials

We provided an illustrated text for the students to read. The article (see Fig. 1) was rewritten from a seventh-year science textbook used in Taiwan (Lin et al., 2008). Its topic was respiration and gas exchange. The article consisted of a title, text section, and diagram section. The text section had 439 Chinese characters in three paragraphs: the first briefly defined respiration; the second described the process of gas exchange during cellular respiration, including examples from several animals; and the third described the respiratory movement of the human body. The diagram section showed two diagrams. The upper one was from the original science textbook



呼吸與氣體的恆定

生物需要能量才能活動，這些能量是從細胞所含的養分分解而來。生物細胞利用氧，將葡萄糖分解並釋放能量，同時也產生了水和二氧化碳，這個過程稱為呼吸作用。

細胞進行呼吸作用時，需與外界進行氣體交換。水中的小生物，例如變形蟲和水螅，可以藉擴散作用，直接從水裡獲得氧氣並排出二氧化碳。較大型的生物因為體內細胞無法直接與外界接觸，因此必須有特殊的構造才能完成氣體交換，例如蚯蚓利用皮膚，魚和貝類利用鰓，鳥類和哺乳類則利用肺，執行跟外界交換氣體的任務。一般而言，呼吸構造要有濕潤的表面以利氧氣融入，且要有充分的血液供應，迅速將氧氣帶至身體各處。

人體與外界交換氣體則是透過呼吸運動。人的肺位於密閉的胸腔。吸氣時，肋骨上舉，橫膈下降，胸腔便會擴大，肺也隨著脹大，此時，肺內的氣體壓力會變小，造成外界空氣進入肺。呼氣時，肋骨肌肉放鬆下降，橫膈舒張上升恢復原狀，胸腔縮小，連帶壓迫到肺，此時肺內壓力變大，迫使氣體排出。劇烈運動時，血液中二氧化碳的增加會刺激腦部，促使加快呼吸運動，藉以排除過多的二氧化碳。

▲利用皮膚呼吸的氣體交換方式

▲人體呼吸運動示意圖

Fig. 1 Six AOIs (*title*, *paragraph 1*, *paragraph 2*, *paragraph 3*, *upper diagram*, and *bottom diagram*) of the reading material. The participants in this study did not see these *black frames*

(Lin et al., 2008), and it depicted gas exchange through the skin of animals, which was related to Paragraph 2 of the text. The lower diagram was obtained from a website (http://www.phyworld.idv.tw), and it depicted the processes of inhalation and exhalation during respiration in humans, which was related to Paragraph 3 of the text.

Three experts verified that the text was suitable for sixth-grade children regarding its difficulty and readability. The first was a professor who was an expert in reading psychology; the second was a PhD candidate in science education; and the third was a science teacher from an elementary school, with a master's degree in science education. We selected the reading material from a textbook written for seventh-grade students rather than from a textbook for sixth-grade students to ensure novelty of the information, which allowed us to investigate how and what students learned while they were reading by themselves. The reading material was displayed on a single screen, and there were no scroll bars or additional pages.

Apparatus

Eye movements of the participants were recorded using Eyelink 1000 at a sampling rate of 1000 Hz. A chin bar was used to minimize head movements. The viewing was binocular, but eye movements were recorded from the right eye only. Eye movements were calibrated and validated until the average error in gaze position was <0.5° of the visual angle. The reading material was presented on a 24-in. LCD monitor with a resolution of 1920 × 1200 pixels. The distance between the monitor and participants was 65 cm. The stimuli on the screen covered 46° of the horizontal visual angle and 30° of the vertical visual angle.

Procedure

This study had three sessions. In the first session, all participants completed the standard reading comprehension screening test (Ko, 1999) and the standard Chinese character recognition test (Huang, 2001). These tests were performed in the classroom, and the procedure lasted for approximately 50 min.

The second session involved the eye movement tracking experiment, which was executed 1 week later. Participants were tested individually in a quiet room in the elementary school, where they were instructed to complete a reading self-efficacy questionnaire (PIRLS, 2011). The questionnaire contained seven items, such as “Reading is easy for me” and “I usually do well in reading.” Students answered each question using a four-point scale ranging from “strongly agree” (1 point) to “strongly disagree” (4 points). Among the seven items, two tested the lack of self-efficacy with a reversed meaning. For these, the answers were scored in reverse (e.g., 4 points was scored as 1 point). Then, the participants read the experimental material to test their comprehension. The experimenter asked the participants to press the space bar on a keyboard when they finished reading to initiate the reading test. There was no time limit set for the reading procedure, in order to simulate natural reading conditions. Therefore, the participants could read at their own pace. Participants first read one practice article and answered several reading-related questions to learn the experimental procedure. After participants indicated that they understood the procedure, the formal experiment was executed. A 12-point calibration and validation procedure was performed for each participant. The experimenter asked the participants to keep their heads still throughout the experimental procedure. When the participants had finished reading, they immediately completed the reading comprehension test, which contained 15 yes/no questions, including five text-based questions, five diagram-based questions, and five integrated questions involving text and diagrams, to investigate their comprehension ability. The questions appeared on the screen, one at a time, and then 11 essay questions were answered on a paper sheet. The essay questions included five “which” questions (e.g., “Which body components of an earthworm conduct respiration?”), three “how” questions (e.g., “How does an organism conduct respiration? Please elaborate on the processes”), and three “why” questions (e.g., “Why does people’s breathing becomes fast when doing strenuous exercise?”). The comprehension test had no time limit. The experimental reading session lasted for approximately 20–30 min.

In the third session, we used questionnaires to measure the participants’ familiarity with the topic and their subjective opinions about the reading material, immediately after the eye movement tracking experiment was complete. First, the experimenter instructed the participants to press a key on the keyboard to indicate whether they had known the meanings of a technical term before reading the scientific article. There were 10 technical terms in the experimental material. If the student knew the meaning of the word, 1 point was awarded; otherwise, 0 points were awarded. One technical term was displayed at a time on the computer screen. Finally, participants completed four questions to evaluate the difficulty of the article, the attractiveness of the article and the diagram, and their own learning performance, using a five-point response scale. All rating tasks were executed on the computer screen, and the procedure lasted for approximately 3–5 min.

Data selection, scoring, and grouping criteria

We collected different data to understand the characteristics and opinions of readers, as well as their cognitive processes and reading performance when reading illustrated text. The former data included a standard Chinese character recognition test, a standard reading screening comprehension test, a self-efficacy questionnaire, a technical vocabulary questionnaire, and an article-rating questionnaire. The latter data included readers' eye movements and a comprehension test after reading the text.

Characteristics and opinions of readers

The data related to readers' characteristics and opinions included the following: (1) the standard Chinese character recognition test contained 200 Chinese characters; each correct answer for writing a pinyin character was awarded 1 point. Higher scores indicate knowledge of a larger number of characters; (2) the standard reading comprehension screening test comprised 20 multiple-choice questions. An example is *Father and mother decide to go to Kenting National Park to go on a honeymoon once again. Which word indicates father and mother has went on a honeymoon? Decide/go to/again/once*. Another example is *Knowing him finally resolved the annoying event, I hastily dry my tears. What is my emotion now? Sad/happy/angry/worried.* Each correct answer was awarded 1 point. Higher scores indicate better reading comprehension ability; (3) the self-efficacy questionnaire contained seven items, with a lower score indicating higher reading self-efficacy, and a higher score indicating lower reading self-efficacy; (4) the vocabulary questionnaire contained 10 scientific technical terms from the reading material. A higher percentage of known terms indicates more familiarity with the topic; and (5) the article-rating questionnaire contained four questions, and self-evaluations of learning performance, which were made on a five-point scale from "very easy/attractive/attractive/good performance" (1 point) to "very difficult/unattractive/unattractive/bad performance" (5 points).

Eye movements

Eye movement data from four participants were excluded due to unsuccessful eye-tracking (two participants) or apparent drift (two participants). Unsuccessful recording occurred due to data transmission failure, and apparent drift occurred when fixations were almost entirely on the blank space, rather than on the text or illustrations. Therefore, the data from 38 participants were included in the analysis. In addition, similar to the procedure used in previous eye-movement studies

(Andrews et al., 2004; Jian, 2016), fixations shorter than 100 ms were excluded, which comprised approximately 5% of the data.

In addition to these eye movement indicators mentioned above, we examined the sequence of eye fixations to investigate the reading strategies adopted by the participants. A series of matrix calculations was carried out for this analysis. First, first-pass transitions (the proportion of first fixations transferred from the initial AOI to the subsequent AOI) were investigated, reflecting the initial processing of target AOIs. For example, if 20 readers first read A-AOI and 10 of them made their next fixations on B-AOI, the transition percentage of first-pass sequences from A-AOI to B-AOI would be 0.50. Second, total-pass transitions (the proportion of total fixations transferred from the initial AOI to the subsequent AOI, which included first-pass and rereading-pass reading types) were calculated, reflecting late processing and higher-order cognitive processing during reading. For example, if A-AOI was read 80 times by 20 readers, and there were 20 transfers to B-AOI, the transition percentage of total-pass sequences from A-AOI to B-AOI would be 0.25. This sequential analysis technique is frequently used to investigate moment-to-moment behavioral sequences (Bakeman & Gottman, 1997), and it has been recently used to analyze eye movement data (Cook et al., 2008a; Jian, 2016; Jian et al., 2014).

Comprehension test after reading the illustrated text

The comprehension test included yes/no questions and essay questions. For the yes/no questions, each correct answer was awarded 1 point. For essay questions, the answers were scored by two independent raters who were blind to the purpose of the study. Inter-rater reliability, which was evaluated with the Cohen's kappa coefficient for each essay question, ranged from 0.90 to 1.00. Each rating disagreement was carefully examined and discussed by the two raters until a consensus was reached. The comprehension test score was calculated as the sum of scores for both question types.

To reveal differences in the characteristics and eye movements of readers with good and poor performance, the participants were divided into two groups according to their comprehension test scores after reading the illustrated text. We sorted all scores of the comprehension test from the highest to the lowest. The first half of all scores were regarded as reflecting good performance, and the latter half poor performance. Each group had 19 participants. Mean scores for the good and poor performance groups were 18.21 ($SD = 4.54$) and 9.42 ($SD = 3.30$), respectively.

Results

The dependent variables were the characteristics of readers (scores on the Chinese character recognition test, reading comprehension screening test, and self-efficacy questionnaire) and eye movement indicators (total reading time, the proportion of fixation durations, mean fixation duration, the frequency of saccade from the text to the diagrams, and the sequence of eye fixations).

Characteristics of readers

The upper section of Table 1 shows that students with good performance had significantly better Chinese character recognition test scores, $t(36) = 2.67, p < 0.05$, $d = 0.87$, and better reading self-efficacy, $t(36) = -3.73, p < 0.01, d = -1.21$, than students in the poorly performing group. However, both groups achieved similar scores on the standard reading comprehension screening test ($p > 0.05$).

The lower section of Table 1 shows that students with good performance rated the diagrams as significantly more attractive, $t(36) = -2.68$, $p < 0.05$, $d = -0.87$, had higher self-evaluated learning, $t(36) = -3.96$, $p < 0.001$, $d = -1.27$, and found the article marginally more attractive, $t(36) = -1.76, p = 0.088, d = -0.57$, than poorly performing students. However, technical vocabularies and ratings of the difficulty of the article were similar in both groups (ps > 0.05).

Eye movement analysis

To investigate processing differences between the students with good and poor performance when reading the illustrated text, we examined various eye movement indicators, including visual attention distribution between the text and diagrams, reference to text and diagrams, and reading pathways. In this regard, according to the Simple View of Reading (Hoover & Gough, 1990), word recognition is an important component of reading comprehension. To avoid the findings for eye movements in the present study being potentially ascribed to group discrepancies in word recognition skills, the scores for a Chinese character recognition test were used for a test of covariance, using ANCOVA for statistical analysis.

Table 1 Reading self-efficacy, Chinese character recognition test, and reading comprehension test for good- and poor-performance groups

	Good-performance group *M* (*SD*)	Poor-performance group *M* (*SD*)	*t*-value
Chinese character recognition test	135.84 (18.95)	120.53 (16.26)	2.67*
Reading comprehension screening test	0.86 (0.10)	0.82 (0.16)	1.04
Reading self-efficacy	12.26 (2.49)	15.26 (2.47)	−3.73**
Know technical vocabularies	0.48 (0.13)	0.45 (0.18)	0.51
Article difficulty rating	2.79 (0.71)	3.16 (0.69)	−1.62
Article likeness rating	1.84 (0.96)	2.42 (1.07)	$-1.76^{\dagger}$
Diagram attraction rating	1.84 (0.83)	2.74 (1.20)	−2.68*
Self evaluation of learning	2.11 (0.46)	2.89 (0.74)	−3.96**

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; † $p < 0.10$

Whole article and detailed component analyses

We first studied the entire article as one AOI and then divided it into three AOIs: title, text, and diagram. The means and standard deviations from the eye-movement analysis are presented in Table 2.

Table 2 shows that the total reading time was significantly longer for students with good performance than for those with poor performance for both the whole article, $F(1, 36) = 13.08$, $p < 0.01$, $\eta^2 = 0.27$, the text section, $F(1, 36) = 10.18$, $p < 0.01$, $\eta^2 = 0.23$, and the diagram section, $F(1, 36) = 10.67$, $p < 0.01$, $\eta^2 = 0.23$. The fixation duration proportions on the text or diagram sections were not significantly different between the groups ($p > 0.05$). It is worth noting that the mean fixation duration on the diagram was significantly longer for students with good performance than for those with poor performance, $F(1, 36) = 8.71$, $p < 0.01$, $\eta^2 = 0.20$. In addition, the group with good performance made significantly more saccades from the text to the diagrams than the group with poor performance did, $F(1, 36) = 9.02$, $p < 0.01$, $\eta^2 = 0.21$.

Analysis of eye fixations sequences

In order to examine cognitive processes and reading strategies in both groups, we carried out a series of sequential matrix calculations (Bakeman & Gottman, 1997) for eye fixations. The time-sequential analysis used an iterative proportional fitting procedure (IPFP) to analyze eye-movement data. According to the definition of

Table 2 Means and standard deviations for eye-movement measures for good- and poor-performance groups

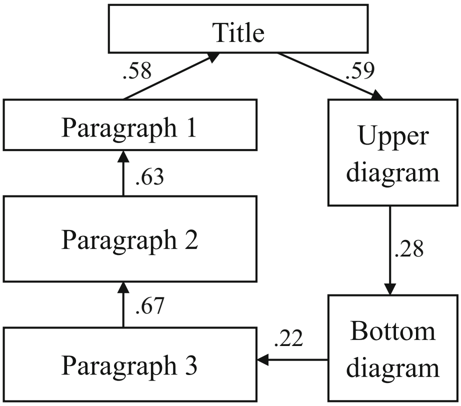
	Good-performance group *M* (*SD*)	Poor-performance group *M* (*SD*)	*F*
Whole article			
Total reading time (s)	208.36 (90.05)	127.81 (74.39)	13.08**
Title section			
Total reading time (s)	1.15 (0.80)	0.80 (1.28)	1.80
Text section			
Total reading time (s)	170.81 (91.77)	107.47 (48.16)	10.18**
Proportion of fixation duration (%)	84 (10)	86 (11)	2.81
Mean fixation duration (ms)	304.73 (49.79)	290.70 (36.24)	1.64
Saccade numbers of text to diagram	5.37 (3.86)	2.68 (2.36)	9.02**
Diagram section			
Total reading time (s)	36.40 (29.72)	19.54 (24.87)	10.67**
Proportion of fixation duration (%)	16 (10)	13 (11)	2.85
Mean fixation duration (ms)	287.29 (42.14)	249.26 (55.04)	8.71**

** $p < 0.01$

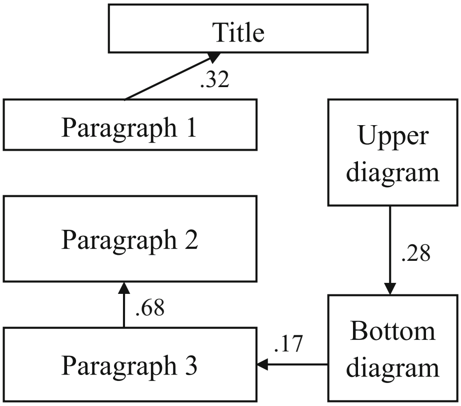
Fiengberg (1970), “IPFP is an iterative algorithm for estimating cell values of a contingency table such that the marginal totals remain fixed and the estimated table decomposes into an outer product.”

We divided the illustrated text into six AOIs: the title, paragraph 1, paragraph 2, paragraph 3, upper diagram, and lower diagram (see Fig. 1). Calculations were performed in accordance with previous studies (Jian, 2016; Jian et al., 2014). We first calculated the fixation transitions among each of the six AOIs in the illustrated text. The adjusted residuals are shown in Tables 3 and 4 in “Appendix”. The rows represent the initial AOIs and the columns represent subsequent AOIs. *Z*-values higher than 1.96, 2.58, and 3.36, indicate that the transfer sequence reached the $p < 0.05$, $p < 0.01$, and $p < 0.001$ cutoff levels for statistical significance, respectively. For example, Fig. 2a indicated that 63% readers of the good-performance group transferred their eye fixations from the paragraph 2 to the paragraph 1 in the first-pass reading, and this percentage was significantly exceeded the expected value, not the outcome of random.

Fig. 2 First-pass transition diagrams for good- and poor-performance groups. The *numbers beside the arrow* indicators show the transition probabilities



(a) Good-performance readers



(b) Poor-performance readers

First-pass and total-pass pathways are reported below. The first-pass pathway reflects participants' initial processing, and the total-pass pathway reflects their late and higher-order cognitive processing.

First-pass fixation sequences in both groups

The first-pass transition diagrams for the students with good and poor performance are presented in Fig. 2; the respective Z-value matrix is shown in Table 3 in "Appendix". We found that groups had both similarities and differences in the reading pathways for the first-pass fixation sequences.

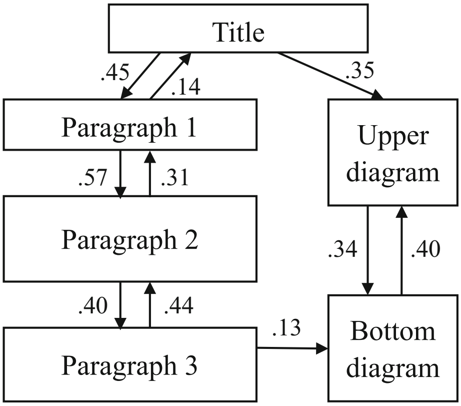
First-pass reading sequences in the groups had two similar characteristics. First, both groups located their fixations on the upper diagram and then transferred their next fixation to the lower diagram. The transfer probability from the upper diagram to the lower diagram was significantly higher than the expected value ($Z = 3.20$, $p < 0.01$ for students with good performance; $Z = 2.42$, $p < 0.05$ for students with poor performance). Second, both groups located their fixations on the lower diagram and then transferred their next fixation to Paragraph 3 of the text. The transfer probability from the lower diagram to Paragraph 3 was significantly higher than the expected value ($Z = 4.13$, $p < 0.001$ for the group with good performance; $Z = 2.73$, $p < 0.01$ for the group with poor performance).

Differences between the groups during the first-pass reading sequences had two characteristics. First, after reading the title for the first time, students with good performance transferred their next fixation to the upper diagram. The transfer probability from the title to the upper diagram was significantly higher than the expected value ($Z = 3.22$, $p < 0.01$); however, students with poor performance did not prefer any particular AOIs in the article after reading the title for the first time ($p > 0.05$). Second, students with good performance read each paragraph of the text and then returned to the previous paragraph (from Paragraph 1 to the title, from Paragraph 2 to Paragraph 1, and from Paragraph 3 to Paragraph 2) after leaving the target area, when they read the text for the first time ($Z = 4.62$, $p < 0.001$; $Z = 3.22$, $p < 0.01$; $Z = 5.43$, $p < 0.001$, respectively). Although students with poor performance also had this tendency, significant effects were present only in the transition from Paragraph 1 to the title ($Z = 3.24$, $p < 0.01$) and from Paragraph 3 to Paragraph 2 ($Z = 3.66$, $p < 0.001$).

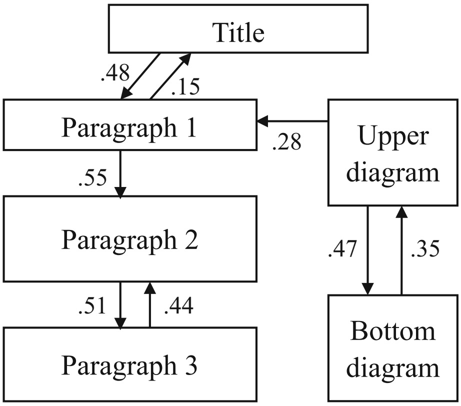
Total-pass fixation sequences in both groups

The total-pass transition diagrams for students with good and poor performance are presented in Fig. 3, and the Z-value matrix is shown in Table 4 in "Appendix". Similar to first-pass fixation sequences, we also found similarities and differences in the total reading pathways of both groups.

Total-pass reading sequence similarities between the groups also had two characteristics. First, overall, both groups interacted more with each paragraph in the text section. Transfer probabilities from the title to paragraph 1 were significantly higher than the expected values ($Z = 3.71$, $p < 0.001$ for the group with good performance; $Z = 4.46$, $p < 0.001$ for the poor-performing group). A



(a) Good readers



(b) Poor readers

Fig. 3 Total-pass transition diagrams for good- and poor-performance groups. The *numbers beside the arrow* indicators show the transition probabilities

similar result was found for the reverse transfer from paragraph 1 to the title ($Z = 5.82$, $p < 0.001$; $Z = 5.46$, $p < 0.001$). Both groups had higher transfer probabilities from paragraph 1 to paragraph 2 than the expected values ($Z = 6.53$, $p < 0.05$ for the group with good performance; $Z = 5.19$, $p < 0.001$ for the group with poor performance). However, the transfer probability for the reverse transfer, from paragraph 2 to paragraph 1, was only significantly higher than the expected value for students with good performance ($Z = 2.79$, $p < 0.01$). Furthermore, both groups had higher transfer probabilities from paragraph 2 to paragraph 3 than the expected values ($Z = 7.29$, $p < 0.001$ for students with good performance; $Z = 6.93$, $p < 0.001$ for students with poor performance). A similar result was found for the reverse transfer from paragraph 3 to paragraph 2 ($Z = 6.73$, $p < 0.001$ for the group with good performance; $Z = 6.36$, $p < 0.001$ for the group with poor performance). Second, both groups transferred their fixations back and forth between the two diagrams, as the transfer probability from the upper diagram to the lower diagram was significantly higher than expected ($Z = 8.57$, $p < 0.001$ for the group with good performance; $Z = 8.70$, $p < 0.001$ for the group with poor performance). A similar result was found for the reverse transfer from the lower diagram to the upper diagram ($Z = 7.78$, $p < 0.001$ for students with good performance; $Z = 5.67$, $p < 0.001$ for students with poor performance).

Differences between the two groups regarding total-pass reading sequences had two characteristics. First, after reading the title, many readers with good performance transferred their next fixation to the upper diagram, with the transfer probability from the title to the upper diagram being significantly higher than the expected value ($Z = 3.36$, $p < 0.01$); however, this preference was not present in the readers with poor performance ($p > 0.05$). Second, the transfer between the text and diagram sections was different between the groups, as the readers with good performance read paragraph 3 and then transferred their next fixation to the lower diagram; therefore, the transfer probability from paragraph 3 to the lower diagram was significantly higher than the expected value ($Z = 2.02$, $p < 0.05$). However, readers with poor performance read the upper diagram and then transferred their next fixation to paragraph 1; therefore, the transfer probability from the upper diagram to paragraph 1 was significantly higher than the expected value ($Z = 2.25$, $p < 0.05$).

Discussion

This study used eye-tracking technology along with several reading tests and questionnaires to investigate reading processes and reader characteristics in sixth-grade readers with good and poor reading performance. We found both similarities and differences between these groups.

Similarities in readers with good and poor performance

This study found several similar characteristics in students with good and poor performance. First, both groups had a similar level of familiarity with the topic of the article; nearly half of all scientific terms used in the article were familiar to both groups, as they expressed that they knew the meaning of these terms before reading the article. The method of using academic terms to test prior knowledge and article familiarity was also used by Liebfreund (2015). Further, both groups in this study had similar reading abilities, according to the reading comprehension screening test (Ko, 1999). Therefore, topic familiarity and reading ability may not have contributed to the between-group discrepancies in learning outcomes that we observed. According to the findings of this study, reading strategies that the readers adopted, the mental effort (reading engagement) invested in reading, and confidence in reading abilities et al. might be the main factors that resulted in different learning outcomes. Some aspects of this finding are consistent with those of Schroeder (2011), who found that 8th and 9th grade students with better comprehension read infrequent concepts more carefully and spent more time on mental model updating while reading. Besides, both groups rated the article difficulty was approximately medium-level difficulty.

Second, both groups had several similar reading pathways. For example, after viewing the upper diagram, which depicted the mechanism of gas exchange through the skin of animals, most readers in both groups transferred their eye fixations to the bottom diagram, which depicted the process of inhalation and exhalation during the respiratory movement, and then they referred to the relevant information in Paragraph 3 of the text section. This result implies that sixth-grade students might have developed the reading strategy of being able to correlate the text and the diagram to some degree, even though their reading abilities are not yet mature. Readers with poor performance correlated irrelevant information (eye fixation from the upper diagram to Paragraph 1). In addition, the eye movement pathways in both groups went back and forth within the text and between the two diagrams, but they rarely crossed between different representations (text and diagrams). The referencing strategy between the text and diagram was, therefore, not developed fully in sixth-grade students compared with adult readers. A recent study (Jian, 2016) found that adult readers refer to the relevant textual and pictorial information in articles with a very high frequency, even if they read a science textbook aimed at primary school students.

Third, both groups mainly relied on the textual information, as opposed to the diagram; the proportion of reading time spent on the text and diagrams were approximately 85 and 15%, respectively. This proportion is in similar to the results of Moore and Scevak (1997); however, an even bigger difference was found by Hannus and Hyönä (1999). Moore and Scevak used think-aloud protocols and found that approximately 13% of their seventh-grade participants reported having used the diagram information when reading the illustrated text. However, Hannus and Hyönä used eye-tracking technology, and found that fourth grade students spent only 6% of their reading time on the diagram section, irrespective of whether their reading abilities were good or poor. However, this proportion was lower in student readers than in adults when reading illustrated scientific texts, as adults spent approximately 70 and 30% of their total reading time on the text and a diagram, respectively (Jian, 2016; Jian & Wu, 2015). These studies suggest the presence of a developmental curve: the older a reader is, the better is his or her diagram literacy. To conclude, these findings suggest that both young and adult readers mainly learned new scientific information via reading descriptions. Reading is driven by the text, rather than by illustrations; readers first integrate the representations of related sentences in the text, and then use diagrams to construct or check their mental model related to this integrated information (Hegarty & Just, 1993).

Discrepancies between readers with good and poor performance

In this study, we also found several apparent differences between the eye-movement patterns and reader characteristics of the participants with good and poor performance. First, sixth graders with good performance were more capable of monitoring their comprehension. Similarly, previous researchers (Oakhill & Cain, 2007; Van der Schoot, Reijntjes, & Van Lieshout, 2012) have found that skilled readers are capable of monitoring their comprehension, and commented that this may result in more regressive eye movements in comparison to less skilled readers. de Leeuw, Segers, and Verhoeven (2016) also found that primary-school students performed more and longer look backs when reading difficult texts. In our study, we demonstrated the presence of this ability from the initial processing stage to the late processing stage of the whole reading process. Sequential analysis of eye movements showed that readers with good performance went back to previous paragraphs (from Paragraph 2 to Paragraph 1, from Paragraph 3 to Paragraph 2) to find relevant semantic information, such as the term “respiration,” when their comprehension was obstructed as they read the text. This phenomenon occurred in both first-pass and total-pass reading sequences.

Second, the diagram literacy of sixth graders with good performance was better than that of sixth graders with poor performance. This study showed that readers with good performance spent twice as much time on viewing the diagrams in the scientific article compared to readers with poor performance. Additionally, students with good performance had longer mean fixation duration on the diagrams than that of students with poor performance. These findings suggest that students with good performance perceived the importance of diagrams in the science article and invested more time and mental effort to encode the diagrammatic information. Furthermore, readers with good performance connected the textual and pictorial representations more frequently, and made more transitions between the text and diagrams in the article. For example, paragraph 3 described human respiration, and the semantically relevant diagram depicted two human bodies during the process of inhalation and exhalation, as well as numerous important parts of the body (e.g., the ribs, lungs, and diaphragm) and their movement status (e.g., ascend, descend, enlarge, and deflate). Readers with good performance had higher transition probabilities between both representations of text and diagrams. This tendency to refer to different representations is consistent with the results of a previous study conducted with fourth-grade student participants. In groups that were divided according to reading ability in advance (Hannus & Hyönä, 1999) and according to reading performance afterwards (Mason et al., 2013a, b), readers with good performance showed more frequent referring behavior between the text and diagrams.

Third, readers with good performance were more interested in diagrams. Sequential analysis of eye movements showed that most readers with good performance observed the diagram after reading the title, but this tendency was not present in readers with poor performance. Based on the data of first-pass reading, we cannot exclude the possibility that the eye fixation of readers was attracted to the diagrams because of their color and shape. Nevertheless, the data of total-pass reading (included first-pass and rereading-pass) showed the same preference in readers with good performance. Therefore, this reading pathway (reading the title being immediately followed by reading the upper diagram) was not only an automatic behavior driven by perceptual stimuli, but also an intentional cognitive behavior, because rereading is a less automatic and more targeted process (Mason et al., 2013a, b, 2015). In agreement with this assertion, Mason et al. (2015) showed that second-pass reading can be used to predict readers’ learning outcomes. In addition, the subjective results of the questionnaire in this study also indicated that readers with good performance were attracted to and liked diagrams.

Fourth, the two groups differed in terms of reader characteristics, especially in the affective dimension. The present results indicate that readers with good performance had higher reading self-efficacy than did those with poor performance. This finding corresponds to that of previous research, which shows that learners' self-efficacy is positively related to reading comprehension (Katzir et al., 2009). The present study also shows that the readers with good performance were more attracted to the diagrams in the learning materials and liked them. This finding implies that reading interest may be related to reading performance (Baker & Wigfield, 1999; Taboada et al., 2009). Furthermore, the readers with good performance in this study were found to self-evaluate their learning outcomes more positively, and were willing to invest more time and effort in engaging in reading episodes.

Conclusion, contributions, and limitations

This study investigated the cognitive processes and reader characteristics of sixth-grade students with good and poor performance when reading illustrated scientific text. Using eye-tracking technology and several reading tests and questionnaires, we found that various cognitive (reading strategy, diagram literacy) and affective (reading self-efficacy, article likeness, diagram attraction, and engagement) aspects affected the students' reading performance.

This study has both theoretical and practical significance. In terms of theory, the present findings extend and contribute to the field of multimedia learning. The theory of multimedia learning (Mayer, 2005) clearly elaborates the cognitive processes of illustrated text reading, but does not mention reader characteristics or affective factors, which may be influential variables in multimedia learning. The findings of this study showed that both cognitive and affective factors might indeed influence reading outcomes, and indicated that reader characteristics like high self-efficacy, interest, engagement, and diagram utilization might have a positive influence on learning performance. However, this study did not determine which variable(s) might be the main factors causing group differences in terms of reading outcomes. Indeed, alternative explanations are possible. According to the simple view of reading (Hoover & Gough, 1990), word recognition ability is an important component of reading comprehension. Thus, this variable may result in group differences in reading outcomes. Although the word recognition ability of the two groups in this study were not paired in advance, their scores on a standard Chinese character recognition test (Huang, 2001) was applied as a covariance in subsequent statistical analysis. After excluding the influence of word recognition ability, the two groups still had many differences in terms of the cognitive processes of illustrated text reading. Therefore, word recognition may not be the only main variable influencing the reading process and learning outcomes. To determine which variable(s) might be a main factor(s), further research is needed to manipulate such variables systematically to determine possible causal relationships.

This study also has practical significance in terms of its educational implications. Using sequential analysis to analyze eye movements facilitates greater understanding of illustrated text reading processes and readers' strategies. For example, the findings showed that readers with good performance had higher transition probabilities of eye fixations to the diagram section after reading the title. Knowing how young students read illustrated texts not only helps primary school teachers to understand the process of reading comprehension among students under various conditions, but also allows them to instruct students more appropriately and help them to develop adequate reading strategies for the future. For example, students might have to learn how to decode pictorial information or to use reference strategies. In sum, we suggested that teachers in the classroom should not only improve students reading strategies but also design teaching activity to trigger students' reading motivation and interests and cultivate their self-efficacy to help them overcome difficulties in reading comprehension.

Some limitations to this study have to be taken into consideration. We used only one biological text with two diagrams; therefore, our findings cannot be generalized to other kinds of diagrams. Visual representations in a scientific article might be formatted as, for example, diagrams, illustrations, photographs, or flow charts. These representations carry different amounts of information displayed in various forms. Because of this diversity, it is difficult to evaluate the effect of several scientific graphs. However, this diversity is typical in scientific articles or textbooks. Future studies need to overcome this limitation. In addition, future research might take advantage of combining eye-tracking technology and the retrospective think-aloud technique (Sung, Wu, Chen, & Chang, 2015; van den Haak, De Jong, & Schellens, 2003). Replaying videos of eye-movement tracks to participants and instructing them to report on what they were thinking might provide more information to help understand reading processes and strategies.

Acknowledgements This study is supported by the Grants MOST103-2511-S-003-065-MY3 and MOST105-2628-H-003-002-MY3 from the Ministry of Science and Technology in Taiwan.

Appendix

See Tables 3 and 4.

Table 3 *Z*-value matrix of the first-pass sequences for good- and poor-performance groups

Target AOI	Title	Paragraph 1	Paragraph 2	Paragraph 3	Upper diagram	Bottom diagram
Start AOI						
Good-performance group						
Title		0.26	−2.05	−1.01	3.22**	−1.36
Paragraph 1	4.62***		−0.88	−1.01	−0.88	−1.36
Paragraph 2	−1.81	3.22**		−1.06	−0.47	−0.50
Paragraph 3	−2.04	−2.65	5.43***		−1.67	−0.15
Upper diagram	0.64	1.10	−2.75	−1.06		3.20**
Bottom diagram	−1.58	−2.33	1.09	4.13***	−0.11	
Poor-performance group						
Title		1.58	−0.75	−0.74	0.40	−1.21
Paragraph 1	3.24**		0.41	−1.01	−0.15	−1.65
Paragraph 2	−1.12	1.58		0.00	0.97	−1.12
Paragraph 3	−1.80	−2.50	3.66***		−1.67	1.28
Upper diagram	0.79	1.23	−2.39	−1.01		2.42*
Bottom diagram	−1.65	−1.65	−0.71	2.73**	1.65	

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 4 *Z*-value matrix of the total-pass sequences for good- and poor-performance groups

Target AOI	Title	Paragraph 1	Paragraph 2	Paragraph 3	Upper diagram	Bottom diagram
Start AOI						
Good-performance group						
Title		3.71***	−2.12	−2.74	3.36**	−2.01
Paragraph 1	5.82***		6.53***	−6.34	−0.64	−4.43
Paragraph 2	−4.14	2.79**		7.29***	−4.64	−5.61
Paragraph 3	−2.87	−4.48	6.73***		−3.66	2.02*
Upper diagram	0.63	1.27	−2.88	−5.01		8.57***
Bottom diagram	−1.45	−4.20	−3.07	1.58	7.78***	
Poor-performance group						
Title		4.46***	−1.88	−2.44	1.38	−1.06
Paragraph 1	5.46***		5.19***	−4.75	−0.67	−3.66
Paragraph 2	−3.04	0.11		6.93***	−3.46	−4.88
Paragraph 3	−2.46	−4.15	6.36***		−2.17	0.24
Upper diagram	0.23	2.25*	−1.90	−3.97		8.70***
Bottom diagram	−1.58	−1.63	−4.60	−0.17	5.67***	

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

References

Ainsworth, S. (1999). The functions of multiple representations. *Computers and Education, 33*(2), 131–152. doi:10.1016/S0360-1315(99)00029-9.

Andrews, S., Miller, B., & Rayner, K. (2004). Eye movements and morphological segmentation of compound words: There is a mouse in mousetrap. *European Journal of Cognitive Psychology*, *16*(1/2), 285–311. doi:10.1080/09541440340000123.

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

Baker, L., & Wigfield, A. (1999). Dimensions of children's motivation for reading and their relations to reading activity and reading achievement. *Reading Research Quarterly, 34*(4), 452–477. doi:10.1598/RRQ.34.4.4.

Bandura, A., & Cervone, D. (1983). Self-evaluative and self-efficacy mechanisms governing the motivational effects of goal systems. *Journal of Personality and Social Psychology, 45*(5), 1017–1028. doi:10.1037/0022-3514.45.5.1017.

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*, 1073–1091. doi:10.1002/sce.20164.

Cook, M., Carter, G., & Wiebe, E. N. (2008a). The interpretation of cellular transport graphics by students with low and high prior knowledge. *International Journal of Science Education, 30*(2), 239–261. doi:10.1080/09500690601187168.

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

Cromley, J. G., Snyder-Hogan, L. E., & Luciw-Dubas, U. A. (2010). Cognitive activities in complex science text and diagrams. *Contemporary Educational Psychology, 35,* 59–74. doi:10.1080/104132001753149883.

de Leeuw, L., Segers, E., & Verhoeven, L. (2016). Role of text and student characteristics in real-time reading processes across the primary grades. *Journal of Research in Reading, 39*(4), 389–408. doi:10.1111/1467-9817.12054.

Evans, J. B. T. (2007). Dual-processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology, 59,* 255–287. doi:10.1146/annurev.psych.59.103006.093629.

Ferk, V., Vrtacnik, M., Blejec, A., & Gril, A. (2003). Students' understanding of molecular structure representations. *International Journal of Science Education, 25*(10), 1227–1245. doi:10.1080/0950069022000038231.

Fienberg, S. E. (1970). An iterative procedure for estimation in contingency tables. *Annals of Mathematical Statistics, 41*(3), 907–917. doi:10.1214/aoms/1177696968.

Grant, E. R., & Spivey, M. J. (2003). Eye movements and problem solving: Guiding attention guides thought. *Psychological Science, 14*(5), 462–466. doi:10.1111/1467-9280.02454.

Guthrie, J. T., & Wigfield, A. (2000). Engagement and motivation in reading. In M. L. Kamil, P. B. Mosenthal, P. D. Pearson, & R. Barr (Eds.), *Handbook of reading research* (Vol. III, pp. 403–422). Mahwah, NJ: Erlbaum.

Hannus, M., & Hyönä, J. (1999). Utilization of illustrations during learning of science textbook passages among low- and high-ability children. *Contemporary Educational Psychology, 24*(2), 95–123. doi:10.1006/ceps.1998.0987.

Harber, J. N. (1983). The effects of illustrations on the reading performance of learning disabled and normal children. *Learning Disability Quarterly, 6*(1), 55–60. doi:10.2307/1510866.

Hegarty, M. (1992). Mental animation: Inferring motion from static displays of mechanical systems. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 18*(5), 1084–1102. doi:10.1037/0278-7393.18.5.1084.

Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of Memory and Language, 32*(6), 717–742. doi:10.1006/jmla.1993.1036.

Hoover, W., & Gough, P. (1990). The simple view of reading. *Reading and Writing: An Interdisciplinary Journal, 2*(2), 127–160. doi:10.1007/BF00401799.

Huang, H. S. (2001). Chinese character recognition test. Psychological Publishing Company **(in Chinese)**.

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. doi:10.1002/rrq.125.

Jian, Y. C., & Wu, C. J. (2015). Using eye tracking to investigate semantic and spatial representations of scientific diagrams during text-diagram integration. *Journal of Science Education and Technology, 24*(1), 43–55. doi:10.1007/s10956-014-9519-3.

Jian, Y. C., Wu, C. J., & Su, J. H. (2014). Learners' eye movements during construction of mechanical kinematic representations from static diagrams. *Learning and Instruction, 32,* 51–62. doi:10.1016/j.learninstruc.2014.01.005.

Johnson, C. I., & Mayer, R. E. (2012). An eye movement analysis of the spatial contiguity effect in multimedia learning. *Journal of Experimental Psychology: Applied, 18*(2), 178–191. doi:10.1037/a0026923.

Katzir, T., Lesaux, N., & Kim, Y. (2009). The role of reading self-concept and home literacy practices in fourth grade reading comprehension. *Reading and Writing*, *22*(3), 261–276. doi:10.1007/s11145-007-9112-8.

Kirby, J. R., Ball, A., Geier, B. K., Parrila, R., & Wade-Woolley, L. (2011). The development of reading interest and its relation to reading ability. *Research in Reading, 34*(3), 263–280. doi:10.1111/j.1467-9817.2010.01439.x.

Ko, H. W. (1999). Reading comprehension-screening test (in Chinese). *Psychological Testing, 46,* 1–11.

Kress, G., & van Leeuwen, T. (1996). *Reading images: The grammar of the visual design*. London and New York: Routledge.

Liebfreund, M. D. (2015). Success with informational text comprehension: An examination of underlying factors. *Reading Research Quarterly, 50*(4), 387–392. doi:10.1002/rrq.109.

Lin, Y. C., Lee, C. S., Huang, N. T., Chang, Y. T., & Tsai, S. F. (2008). Living science and technology textbook. Kang Hsuan Company Press.

Mason, L., Pluchino, P., Tornatora, M. C., & Ariasi, N. (2013a). An eye-tracking study of learning from science text with concrete and abstract illustrations. *Journal of Experimental Education, 81*(4), 356–384. doi:10.1080/00220973.2012.727885.

Mason, L., Tornatora, M. C., & Pluchino, P. (2013b). Do fourth graders integrated text and picture in processing and learning from an illustrated science text? Evidence from eye-movement patterns. *Computers and Education, 60*(1), 95–109. doi:10.1016/j.compedu.2012.07.011.

Mason, L., Tornatora, M. C., & Pluchino, P. (2015). Integrative processing of verbal and graphical information during re-reading predicts learning from illustrated text: An eye-movement study. *Reading and Writing, 28*(6), 851–872. doi:10.1007/s11145-015-9552-5.

Mayer, R. E. (2005). *The Cambridge handbook of multimedia learning*. New York, NY: Cambridge University Press.

McTigue, E. M. (2009). Does multimedia learning theory extend to middle-school students? *Contemporary Educational Psychology, 34*(2), 143–153. doi:10.1016/j.cedpsych.2008.12.003.

McTigue, E. M., & Flowers, A. C. (2011). Science visual literacy: Learners' perceptions and knowledge of diagrams. *The Reading Teacher, 64*(8), 578–589. doi:10.1598/RT.64.8.3.

Miller, B. W. (2015). Using reading times and eye-movements to measure cognitive engagement. *Educational Psychologist, 50*(1), 31–42. doi:10.1080/00461520.2015.1004068.

Moore, P. J., & Scevak, J. J. (1997). Learning from texts and visual aids: A developmental perspective. *Journal of Research in Reading, 20*(3), 205–223. doi:10.1111/1467-9817.00033.

Norman, R. R. (2012). Reading the graphics: What is the relationship between graphical reading processes and student comprehension? *Reading and Writing, 25*(3), 739–774. doi:10.1007/s11145-011-9298-7.

Oakhill, J., & Cain, K. (2007). Issues of causality in children's reading comprehension. In D. McNamara (Ed.), *Reading comprehension strategies: Theories, interventions, and technologies* (pp. 47–72). New York, NY: Erlbaum.

Paivio, A. (1990). *Mental representations: A dual coding approach* (pp. 53–83). New York, NY: Oxford University Press.

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

Reid, D. J., & Beveridge, M. (1986). Effects of text illustration on children's learning of a school science topic. *The British Journal of Educational Psychology, 56*(3), 294–303. doi:10.1111/j.2044-8279.1986.tb03042.x.

Rusted, J., & Coltheart, M. (1979). Facilitation of children's prose recall by the presence of pictures. *Memory and Cognition, 7*(5), 354–359. doi:10.3758/BF03196939.

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

Schroeder, S. (2011). What readers have and do Effects of students' verbal ability and reading time components on comprehension with and without text availability. *Journal of Educational Psychology, 103*(4), 877–896. doi:10.1037/a0023731.

Schunk, D. H. (1981). Modeling and attributional effects of children's achievement: A self-efficacy analysis. *Journal of Educational Psychology, 73*(1), 93–105. doi:10.1037/0022-0663.73.1.93.

Segers, E., Verhoeven, L., & Hulstijn-Hendrikse, N. (2008). Cognitive processes in children's multimedia text learning. *Applied Cognitive Psychology*, *22*, 375–387.

Slough, S., & McTigue, E. (2010). Introduction to the integration of verbal and visual information in science texts. *Reading Psychology, 31*(3), 206–212. doi:10.1080/02702710903241397.

Small, M. Y., Lovett, S. B., & Scher, M. S. (1993). Pictures facilitate children's recall of unillustrated expository prose. *Journal of Educational Psychology, 85*(3), 520–528. doi:10.1037/0022-0663.85.3.520.

Sung, Y. T., Wu, M. D., Chen, C. K., & Chang, K. E. (2015). Examining the online reading behavior and performance of fifth-graders: Evidence from eye-movement data. *Frontiers in Psychology, 6,* 1–15. doi:10.3389/fpsyg.2015.00665.

Taboada, A., Tonks, S. M., Wigfield, A., & Guthrie, J. T. (2009). Effects of motivational and cognitive variables on reading comprehension. *Reading and Writing, 22*(1), 85–106. doi:10.1007/s11145-008-9133-y.

Unrau, N. J., & Quirk, M. (2014). Reading motivation and reading engagement clarifying commingled conceptions. *Reading Psychology, 35*(3), 260–284. doi:10.1080/02702711.2012.684426.

van den Haak, M. J., De Jong, M. D. T., & Schellens, P. J. (2003). Retrospective vs. concurrent think-aloud protocols: Testing the usability of an online library catalogue. *Behavior and Information Technology, 22*(5), 339–351. doi:10.1080/0044929031000.

Van der Schoot, M., Reijntjes, A., & Van Lieshout, E. C. M. D. (2012). How do children deal with inconsistencies in text? An eye fixation and self-paced reading study in good and poor reading comprehenders. *Reading and Writing, 25*(7), 1665–1690. doi:10.1007/s11145-011-9337-4.

Wigfield, A., Guthrie, J. T., Perencevich, K. C., Taboada, A., Klauda, S. L., McRae, A., et al. (2008). Role of reading engagement in mediating effects of reading comprehension instruction on reading outcomes. *Psychology in the Schools, 45*(5), 432–445. doi:10.1002/pits.20307.