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# Eye Movements in Integrating Geometric Text and Figure: Scanpaths and Given-New Effects

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**Abstract** This study explored the processes in which adult readers integrate text-figure information when reading geometric descriptions. Because geometry conveys rich spatial information, we investigated the reading scanpaths as text- or figure-directed and the given-new effects. Eye movement data from 65 college student participants showed that approximately 1% inspected the figure-first, while the other displayed the text-first which included 86% displayed the text-directed. Although the descriptions that violated the given-new ordering did not affect the accuracy of the test, they did increase reaction time, figure-fixation duration, and the number of saccades from text to figure. The transition paths showed that the participants shifted their fixations to the figure to refer to corresponding elements when they encountered new geometric elements in the text. The descriptions that violated the given-new ordering influenced the reading processes and efficiency. These findings indicate that although the readers spent 40% fixation duration on figure, their reading pattern was text-directed, and the word ordering of description affects integration of geometric text and figure.

**Keywords** Eye movement · Geometric reading · Given-new ordering · Scanpath

## Introduction

In geometric reading, readers have to process the information in the text and figure to comprehend its meaning. Owing to its concentration and spatialization, geometric text is difficult to comprehend (Duval, 1995, 1998; Gal & Linchevski, 2010). How does the reader integrate information from the text and figure in an illustrated geometric text? Is the reading pattern text- or figure-directed? How does the word order of the geometric text influence reading processing and comprehension? The answers to the above

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questions are not only important for reading theory on illustrated text but also have implications for mathematics education. The measurement of eye movements provides us with moment-to-moment processing and valuable insight into participants' visual attention while reading mathematics (Andrá, Lindström, Arzarello, Holmqvist, Robutti & Sabena, 2015; Chen & Wu, 2012; Epelboim & Suppes, 2001; Susac, Bubic, Kaponja, Planinic & Palmovic, 2014).

It is important to clarify the way in which a reader integrates figures and text. Prior studies have indicated that text plays the dominant role in the reading of science articles containing both figures and text (Hannus & Hyona, 1999; Hegarty, 1992; Hegarty & Just, 1993). However, geometry is the study of shape and space in which representing and transforming figural information is used to develop concepts and arguments (Duval, 1995; Gal & Linchevski, 2010). Moreover, the eye movement data from reading geometric proofs and problem solving showed that high ratio of the fixation durations was on figures (Chen & Wu, 2012; Lin & Lin, 2014). These results suggest that readers rely considerably more on figures in geometry than those in science. The primary focus of this study is thus to determine whether geometry reading is text- or figure-directed.

If the reading pattern for geometric descriptions remains text-directed, as seen in the majority of previous studies in science, this would imply that word ordering of written descriptions influences reading processing and comprehension. Based on given-new ordering theory (Clark & Haviland, 1977; Ferreira & Yoshita, 2003), new information must be based on given information for communication to be effective. However, according to our own survey, the majority of illustrated geometric descriptions in Taiwanese textbooks is not presented in a manner consistent with given-new ordering. The second focus of the present study is thus to explore how this incongruence between word ordering in geometric descriptions and given-new ordering affects the reader's performance.

## Reading Theory: Integrating Text and Figures

Decoding and comprehension are two major processes in reading comprehension (Hoover & Gough, 1990). Decoding is treated as a basic process for word recognition that allows access to the mental lexicon and retrieval of the word's semantic information. Comprehension is a higher-level process that involves the integration of words and the construction of a mental model of the text. Similarly, some theories of figure comprehension argue that two cognitive components are required to establish a representation of a figure (Carpenter & Shah, 1998; Ratwani, Trafton & Boehm-Davis, 2008). Pattern recognition (or visual integration) leads to the encoding of a pattern by composing a visual chunk, and the interpretation (or cognitive integration) compares these visual patterns and translates them into quantitative or qualitative meanings. Therefore, the components of decoding and comprehension were used to analyze the processes of reading illustrated text.

Mayer's multimedia learning theory (1997) suggests five cognitive processes in multimedia learning: selecting relevant words from the verbal channel, selecting relevant images from the pictorial channel, organizing the selected words into a verbally based model, organizing the selected images into a pictorially based model, and integrating word-based and image-based representations with prior knowledge.

Mayer assumed that meaningful learning occurs when learners select information from previously read content, organize different forms of information into a coherent mental representation, and integrate this new representation with their existing knowledge structures. A similar suggestion for an integrated model of text and picture comprehension was proposed by Schnotz and Bannert (2003). They proposed that the task-relevant information in a text is selected and transformed into a text-surface representation through verbal organization, from which it is further transformed into a propositional representation by way of semantic processing. By contrast, in figure comprehension, readers first engage in perceptual processing, which includes the identification and discrimination of graphics. Gestalt laws then apply to the process of visual organization to create a visual perception. However, the final mental model formed by an individual does not completely adhere to the results of visual perception because it undergoes an intermediary schema-driven mapping process. Individuals may directly obtain information from a figure and thereby form a mental model (bottom-up); alternatively, a mental model may be formed by the active interpretation of figures through a cognitive schema (top-down). The propositional representation formed through text comprehension continuously interacts with the mental model formed through figure comprehension.

According to Schnotz and Bannert's (2003) theory, the incorporation of figures into text provides an advantage via an additional mode of encoding, allowing the two processes to act in a complementary fashion. This occurs because the propositional representation and mental model belong to different sign systems and operate under different representation principles. This theory differentiates the sensory-level channels (visual and auditory) and cognitive-level representational channels (verbal and pictorial) such that the comprehension of different types of information entails combining different sensory and representational channels. Most theories agree that the mental model produced during the inspection of a multimedia object is the outcome of the interaction between, and integration of, the various cognitive systems employed in processing the text and figures, etc. Nevertheless, when figure and text representations are established, is there a difference in sequence? Moreover, which begins first, and under what circumstances do they interact?

## Text- or Figure-Directed: Evidence from Eye Movements

Several previous studies exploring figure-text reading in the context of scientific information or advertisements have found that reading behavior appears largely text-directed. Hegarty and Just (1993) used eye tracking to explore the integration of figure-text information in the construction of a mental model of a pulley system. They observed that the participants repeatedly read the words that described the crucial parts or the relations between the parts. This implies that readers established a text-based representation prior to inspecting the figures when creating the complete mental model. From local to multipart global inspections, the main purpose of figure inspection is to confirm the spatial relations and kinetic information presented in the textual description. This study also noted the significance of the timing of interruptions between text reading and figure investigation. In the case of a reader inspecting a figure after reading a sentence or processing a new piece of information, this pointed to his or her intention to obtain more graphic or spatial information for the purposes of constructing a mental model. In the case that a reader inspected a figure after processing the entire text, he or she first established a text-based representation or mental model. The study thus showed that readers' mental models are constructed by both text and figures, by text or figures alone, or first by text and then by figures.

Similar results were obtained from different studies with different materials and participants. With regard to scientific texts, Schmidt-Weigand, Kohnert and Glowalla (2010) examined how college students split their visual attention in multimedia learning. They observed that learners started text before alternating between text and dynamic illustration, spending more time looking at text than at illustration. Hannus and Hyona (1999) examined the role of illustrations for children reading biology textbooks. Their results showed that children spent a considerably shorter amount of time (6%) on illustrations. Moreover, the correlation between the children's memory of illustrations and the time they spent on text was stronger than the correlation between the children's memory of illustrations and the time they spent on illustrations. Even in the context of advertisements, where the image is essential, text-directed reading patterns are still observed. Rayner, Rotello, Stewart, Keir and Duffy (2001) found that although some participants would glance at a figure before reading the text, the movement was only cursory. Most participants first read the text and then made a detailed examination of the figure. This result suggests that reading patterns are still text-directed in primarily pictorial material such as advertisements. Thus, it appears that early attention given to text may be a longstanding strategy when viewers process stimuli with textual and pictorial information.

However, the eye movement data suggested that geometric reading is heavily focusing on figure. Chen and Wu (2012) collected eye-tracking data from 31 college students reading geometric proofs and studied their ratio of figure-text inspection. The results showed that ratios of the total fixation duration spent on figure for four proof worked examples were 38 to 61%. In addition, fixation in milliseconds per pixel for the figure segment (0.21 – 1.32) was significantly longer than that of the text segment (0.15 – 0.36). These results demonstrate that readers are heavily reliant on figures when reading geometric proofs. Lin and Lin (2014) used an eye tracker with handwriting devices to investigate $11^{th}$-grade students' eye movements while solving geometry problems. All five problems required students to solve for the length of a specific side of two similar triangles. Each problem consisted of a brief text, consisting of a given statement and a question sentence, and a figure with paired similar triangles that were labeled with a given digit and question mark. The on-screen fixations were separated into three areas of text, figure, and calculating area. The results demonstrated that the total dwell time within the text area was far less than within the figure or calculating areas. Furthermore, a positive relationship was discovered between perceived difficulty and fixation counts, dwell time, and run counts in the figure area. In their research, some tasks required translation or mental rotation of the figure. Therefore, the readers relied more on the figure than the text.

In contrast, a small amount of scanpath evidence in problem solving has suggested that geometric reading is text-directed. Epelboim and Suppes (2001) used participants' eye movements and protocol to observe three adult scanpaths while solving geometric word problems. According to participants' protocol, their paths to the solution were divided into several stages. During the different stages, their fixations tended to be on protocol-relevant elements more frequently than those on other elements. Although the fixation patterns in later stages depended on participants' expertise, all three participants began working on each problem by reading the text and referring to the relevant elements in the figure. Based on the limited sample size in that article, geometric reading seemed to be text-directed in problem-solving.

Duval (1995) has suggested that humans cannot solely depend on perceptual identification in order to fully comprehend a geometric figure. He proposed that the processing of geometric figures includes perceptual, sequential, discursive, and operative apprehensions. When interpreting a geometry question, a reader must rely on the mathematical properties of geometric components as well as on the relevant information contained in the description prior to constructing a complete propositional representation; an exclusive reliance on geometric-figure recognition will not allow the individual to understand the meaning of the question.

On overview of the literatures supporting text-directed pattern reveals that the majority of research has focused on science article reading. We know relatively little about the reading pattern of geometric descriptions. Whether readers first use text to construct their preliminary representation and then integrate it with information from figures, or vice versa, thus requires further inquiry.

## Given-New Ordering

What manner of description makes for effective communication? According to the given-new ordering theory proposed by Clark and Haviland (1977; Haviland & Clark, 1974), communication is a cooperative process between a speaker and listener. Before producing new information, the speaker must identify what the listener already knows (the given information). The listener must first distinguish the given information from the novel information, find the direct antecedent already present in memory, and then integrate the new information into the memory (Haviland & Clark, 1974; Vande Kopple, 1982). For example, the sentence, "The jokes Horace tells are awful," conveys two pieces of information: the given information that the speaker assumes the listener already know is "Horace tells jokes"; the new information that the speaker wants to convey is "the jokes are awful." If the listener holds the antecedent "Horace tells jokes" in memory, he or she may incorporate the new information (i.e. "the jokes are awful") with it, effectively comprehending the precise meaning of the new information. It is apparent that presenting given information as an antecedent is critical to understanding new information. If there is no suitable antecedent, the listener needs to find one or must build some form of bridging structure (Haviland & Clark, 1974). This requires more time and effort, which increases the listener's memory load and complicates comprehension, potentially detracting from it (Clark & Haviland, 1977). According to the given-new ordering, effective communication occurs when the speaker is aware of what the listener already knows and conveys novel information on the basis of such given information.

The effect of given-new ordering has been observed when using pairs of sentences (as in Clark and Haviland's studies) and in reading regular articles (Vande Kopple, 1982). Below are two descriptions commonly seen in Taiwanese junior high school mathematics textbooks:

1. ΔABC 中,在 $\overline{AC}$ 上作垂直線 $\overline{BD}$
   ΔABC chung, tsai $\overline{AC}$ shang tso ch'ui chih hsien $\overline{BD}$
   In ΔABC, the perpendicular drawn to $\overline{AC}$ is $\overline{BD}$
2. ΔABC中, $\overline{BD}$ 為 $\overline{AC}$ 上的垂直線
   ΔABC chung, $\overline{BD}$ wei $\overline{AC}$ shang te ch'ui chih hsien
   In ΔABC, $\overline{BD}$ is perpendicular to $\overline{AC}$

While these two descriptions appear to be quite similar (as is the information they transmit), they differ when analyzed according to given-new ordering. In both instances, "In ΔABC" is a contextual part presenting the first piece of information a reader receives. In the first instance, "along $\overline{AC}$ draw a vertical line $\overline{BD}$" is the following part, since $\overline{AC}$ has been constructed from the structure of the contextual part and is the antecedent already present in memory. The reader can attach the new information (vertical line $\overline{BD}$) to the antecedent, thereby integrating the new information with the given, already processed, information.

In the second instance, the appearance of new information ($\overline{BD}$) in the following part prior to the given information ($\overline{AC}$) violates the communication principle of given-new ordering. If a reader were unable to locate a suitable antecedent to integrate existing and new information, he or she would be forced to memorize this information, stop reading the text, shift fixations to the figure segment, and seek the bridging information from the figure. This would lead to an increase in cognitive load, potentially influencing both reading time and the comprehension process.

Based on two editions of Taiwanese junior high school mathematics textbooks published in 2011, we tabulated the ratio of all the geometric descriptions consistent with given-new ordering. Two conditions were used to filter the descriptions. First, the description had to be an illustrated geometric text. That is, the description had to contain both geometric figures and a textual description. Second, the description had to contain both contextual and following part. Whether the overall description was taken to be consistent with given-new ordering depended on the sequencing of information in a continuation sentence. If given information appeared before new information in a continuation sentence, that sentence was consistent with given-new ordering; if it did not, the question was assumed to violate given-new ordering. The sorting results revealed that the ratio of geometry questions consistent with given-new ordering was 7/33 (21%) in one textbook and only 3/30 (10%) in the other. The low ratio of consistency with given-new ordering highlights the importance of investigation of the ordering effect on geometry reading.

## Research Questions and Hypotheses

The first question examined in the present study is whether the reading process of geometric descriptions is text- or figure-directed. Geometric descriptions are similar to geometric problems; however, they do not pose a question. Most previous research has found that reading an illustrated text is text-directed. We doubt whether the reading process of illustrated geometric text is different due to the importance of the geometric figure, which supports the construction of a mental configuration. If a reader initially inspects a figure segment with a minimum of three fixations, the movement indicates a figure-directed reading pattern. In this case, we may conclude that the act of inspecting a figure drives the subsequent act of text reading. Otherwise, we may conclude that people's reading of illustrated geometric texts remains text-directed. In order to answer this question, we used eye-tracking technology to record readers' eye movement patterns.

The second question addressed in this study is whether the consistency of an illustrated geometric text with given-new ordering influences comprehension or reading processes. Besides the accuracy of a participant's answer to the question and reaction time, we consider certain eye movement indices to investigate the effect, such as fixation duration, the number of saccades from text to figure, and the ratio of figure fixation duration to total fixation duration. Since geometric descriptions that are consistent with given-new ordering enable readers to process a text segment fluently, we expected readers in a given-new (GN) version to exhibit higher accuracy in their answers, shorter reading time, and a lower reliance on figure-segment information than readers in a non-given-new (NGN) version. Therefore, the total fixation duration, the number of saccades from text to figure, and the ratio of figure fixation duration of the group GN were predicted to be less than those of the group NGN. In addition, the reading scanpaths of the groups GN and NGN were expected to be different.

## Method

### Participants

The participants were 68 students of the National Taiwan Normal University, majoring in educational psychology, social science, education, and the arts. We excluded students who majored in mathematics. Data from three participants were excluded because of eye drift. However, adequate samples were obtained from the remaining 65 participants.

### Materials

The materials comprised nine geometric descriptions and nine yes/no questions. In typical Taiwanese textbooks, the layout includes descriptions with a text segment on the left and a figure segment on the right. Every text segment had two versions: the given-new (GN) version and the non-given-new (NGN) version (see Fig. 1). The text segment for the GN version was written in accordance with given-new ordering, and that accompanying the NGN version was written in violation of that ordering. The figure segments for both versions were the same.

Each description was followed by a true-false question to ascertain the participants' understanding and prompt them to read serially. For example, following the item in

Fig. 1, the participants were asked to judge whether "$\overline{BE} = \overline{BD}$" was true or false. The questions for both versions were the same. The probability of true and false answers to all questions was close to 50%.

**Apparatus**

Participants' eye movements were recorded with an Eyelink 1000 eye tracker at a sampling rate of 1000 Hz. A chin bar was used to minimize head movement. Each item was composed of both text and figure, which were displayed on a 19-inch monitor with a display resolution of 1024 × 768 pixels. The text segment of an item was approximately 22 × 30 cm (814 × 1110 pixels) in area, and the figure segment of an item was approximately 23 × 30 cm (851 × 1110 pixels) in area. The participants sat approximately 65 cm away from the monitor. The complete reading article covered 40° horizontal and 32° vertical visual angles.

**Procedure**

The participants were tested individually. They were instructed to read several geometric descriptions and then complete a number of true/false comprehension questions. Once the participants finished reading a description, they could press a key on the keyboard to leave the reading stage and start the comprehension question; if they did not press a key, the description remained for least 60 s, with every question displayed for a maximum of 30 s. In order to provide natural reading conditions, the duration was estimated to be sufficient for both reading the text and answering the question based on

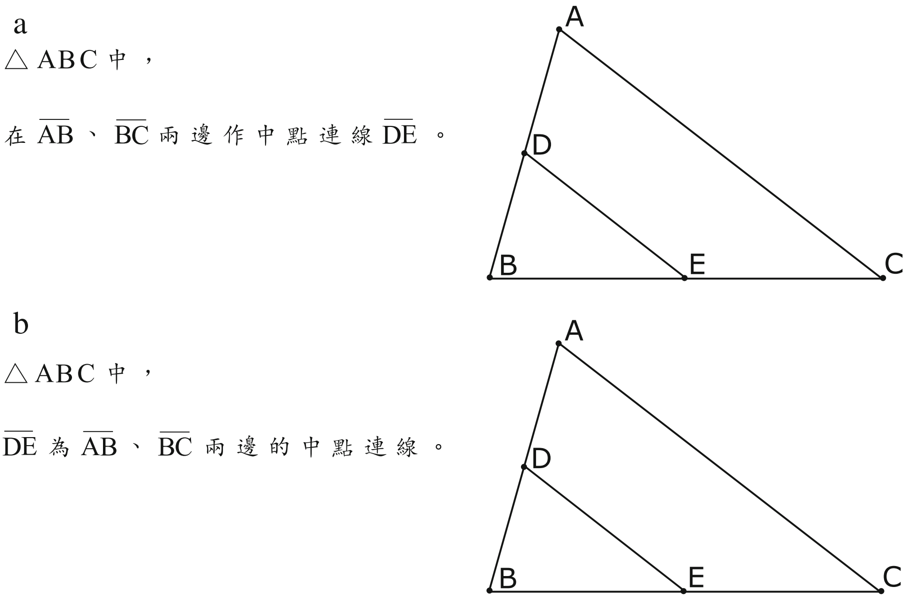


**Fig. 1** Examples of the reading material in GN version (**a**) and NGN version (**b**). (Line DE is the midsegment joining the midpoints of side AB and side BC.)

a previously conducted pilot study. After the introduction, the participants had a practice session.

Following eye movement calibration and verification, the formal experiment was conducted. The presentation order and versions for the nine items were randomly assigned to the participants. Eye movements while reading the geometric descriptions and the reaction time for each comprehension question were simultaneously recorded. The experiment lasted for approximately 20 min.

## Results

### Text- or Figure-Directed?

There were a total of 534 instances of data analyzed for reading patterns. Some instances (51/585) of eye movement data were excluded due to apparent drift and signal reception problems. We categorized participants' eye movement as figure-first and text-first patterns. If a participant first inspected the figure at a minimum of three fixation points, it was classified as figure first (Fig. 2, the dots with numbers indicate readers' fixation sequences); the remainder were classified as text first. The text-first instances were further divided into text-directed and "other" patterns. If the participants first looked at the text segment, then referred to the corresponding elements of the figure, immediately afterward returning to the text segment, these instances were classified as text-directed. Figure 3 demonstrates that the first three fixations moved according to the sequence of the text description; when arriving at "$\overline{DE}$" (fixation 4), the fixations shifted from the text to point $D$ in the figure and alternated between points $D$ and $E$ (fixation points 5 to 8). Upon locating "$\overline{DE}$" in the figure, the fixations returned to the text (points 9 and above), at which point the participants continued reading. The agreement of two raters was 93% (50/54), and the inter-rater reliability was acceptable with Kappa values of 0.73 ($p < .001$).

The outcome revealed that only three instances (0.6%) were figure first. Among the remainder text-first cases, we observed that 457 instances (85.6%) belonged to text-directed and 74 instances (13.9%) that we referred to as other text first. The results showed that most reading patterns for geometric descriptions were text-directed.

There were different sub-patterns in other text-first patterns. For example, some instances showed that the participants finished reading the text segment before moving to the figure. In those cases, most of the text descriptions were short. We may infer that the short text descriptions did lead to a mild memory load, as the participants did not

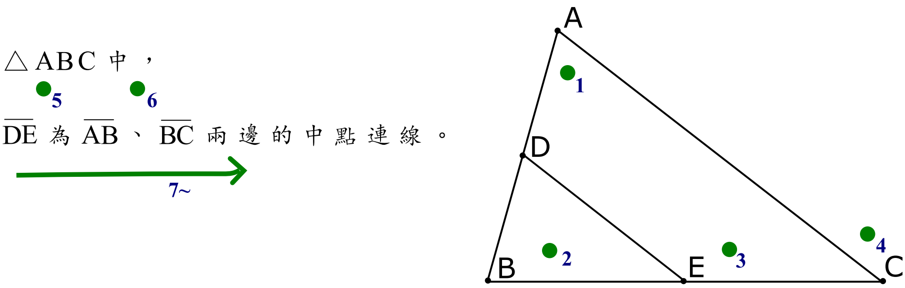


**Fig. 2** An illustration of a figure-first pattern

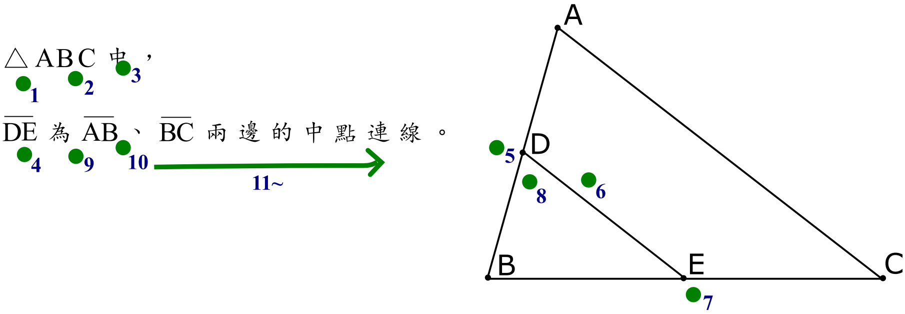


**Fig. 3** An illustration of a text-directed pattern

interrupt their reading of the text to inspect the figures. Some other instances showed that when the participants referred from the text to the figure, they did not only fixate on the corresponding elements but also on other elements.

## Effects of Given-New Ordering

We carried out a series of behavior and eye movement analyses to evaluate the given-new effects. The behavior analyses involved measuring the accuracy and reaction time of the nine true/false questions. The eye movement analyzes were based on measurements of item reading included the fixation duration (FD), the number of saccades from text to figure, and the ratio of figure fixation duration. Referring to previous eye-tracking research (Chen & Wu, 2012), we excluded fixations shorter than 100 ms. Means and standard deviations of accuracy, reaction time, and eye movement measurements are shown in Table 1. The valid instances were dependent on different measurements.

**Accuracy of Question Answer.** The accuracy of true/false questions ranged from 0.55 to 0.97, with an average of 0.86. This indicates that most of the participants were correctly able to answer the questions. A between-subject design 2 (version) × 9 (item) ANOVA was performed on the accuracy data. The main effect of item was significant, $F(8, 565) = 9.98$, $p < .001$, $\eta^2 = .12$. However, there was no main effect of version, nor was the interaction effect between version and item significant, *p*s > .10.

**Table 1** Means and standard deviation for accuracy, reaction time, and eye movement measures for the GN and NGN groups

| | Given-new | Non-given-new |
|---|---|---|
| | *M* (SD) | *M* (SD) |
| Accuracy of test | 0.87 (0.02) | 0.85 (0.02) |
| Reaction time (s) | 9.49 (0.19) | 10.11 (0.19) |
| Total FD on text (s) | 4.32 (0.11) | 4.39 (0.11) |
| Total FD on figure (s) | 2.41 (0.08) | 2.85 (0.08) |
| The number of saccades from text to figure | 4.49 (0.11) | 5.06 (0.11) |
| The ratio of figure FD (%) | 35.81(12.01) | 39.36 (11.53) |

**Reaction Time.** Reaction time is the duration from the presentation of a question until the participant presses the yes or no button. A between-subject design 2 (version) × 9 (item) ANOVA on the average reading time revealed a significant main effect of version, $F(1, 545) = 5.16$, $p = .02$, $\eta^2 = .009$; the reading time was shorter in the GN version than that in the NGN version. There was a significant main effect of item, $F(8, 545) = 28.59$, $p < .001$, $\eta^2 = .296$, but there was no interaction effect, $p > .10$.

**Fixation Duration on Text Segment and Figure Segment.** A 2 (version) × 2 (segment) × 9 (item) ANOVA was performed on the average fixation duration. The three-way interaction was not found to be significant, $F(8, 545) = .99$, $p > .10$. The interactions between item and segment, $F(8, 545) = 5.91$, $p < .001$, $\eta^2 = .08$, or version and segment, $F(1, 545) = 6.14$, $p = .01$, $\eta^2 = .01$, were both significant. As we do not focus on the difference between items in this article, we merely conducted a simple main effect test of version and segment. This indicated that the text-fixation duration was longer than the figure-fixation duration in both the GN and NGN versions, $F(1, 280) = 315.28$, $p < .001$, $\eta^2 = .53$; $F(1, 281) = 212.51$, $p < .001$, $\eta^2 = .43$, respectively. The text-fixation duration in the GN version (4.32 s) did not differ from that of the NGN version (4.39 s), $p > .10$. Nevertheless, the figure-fixation duration in the GN version (2.41 s) was shorter than that in the NGN version (2.85 s), $F(1, 561) = 11.24$, $p = .001$, $\eta^2 = .02$.

**The Number of Saccades from Text to Figure.** This measurement is based on the total number of times of fixation move from text to figure. A between-subject design 2 (version) × 9 (item) ANOVA on the number of saccades from text to figure revealed a main effect of version, $F(1,524) = 12.77$, $p < .001$, $\eta^2 = .024$; the number of saccades from text to figure in the GN version (4.49 times) was less than that in the NGN version (5.06 times). There was a significant main effect of item, $F(8, 524) = 20.15$, $p < .001$, $\eta^2 = .24$, but there was no interaction effect, $p > .10$.

**Ratio of Figure Fixation Duration.** This measurement refers to the percentage of the fixation duration on the figure of the total fixation duration. There was no difference in the ratio of figure-fixation duration between the group GN and group NGN, $p > .10$. As a whole, the participants spent approximately 40% of the total fixation duration on the figure.

**Scanpath.** Using Markov transition probability, the transition paths of the fixations between words and figure were examined for the two versions. The Markov transition matrix counts the sequence of fixations and translates them into conditional probabilities (Henderson, Falk, Minut, Dyer & Mahadevan, 2001). Before analysis, all texts were parsed by a Chinese word segmentation system designed by Chinese Knowledge and Information Processing (Academia Sinica Taiwan, 1999). Every Chinese word was an interesting area (IA), while every point of the figure in each description was a stand-alone IA. As shown in Fig. 4, the arrows displayed the highest probability scanpath from every IA. If the most likely next fixation stayed on the initiate IA, a circle replaced an arrow.

As Fig. 4 demonstrates, the transition paths of text-figure reference of the two versions showed certain similar patterns. In the first, the participants of both the

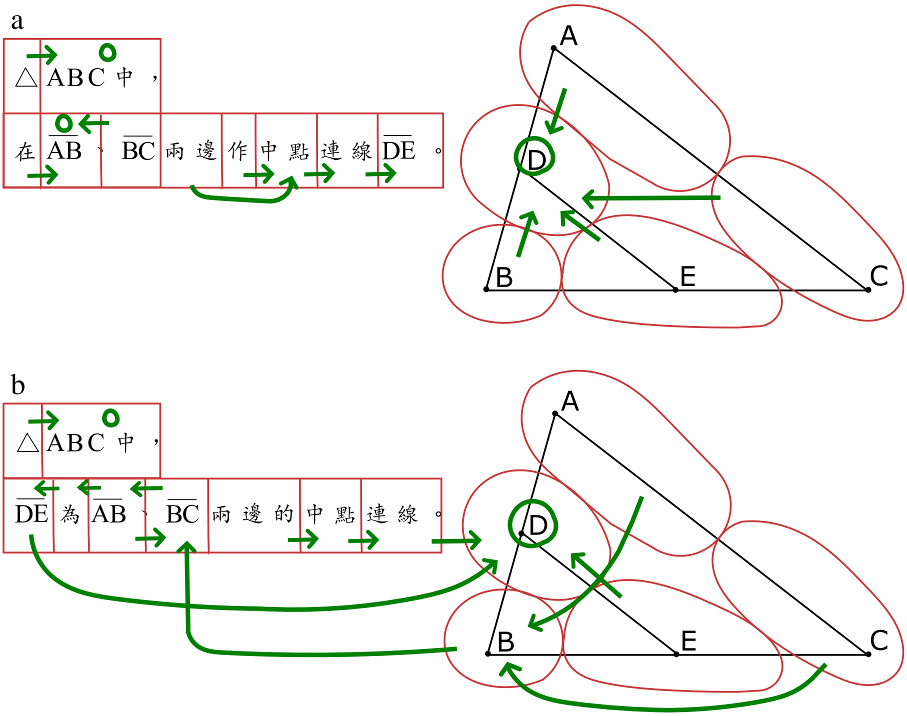


**Fig. 4** A comparison of scanpaths in the GN version (**a**) and NGN version (**b**)

groups did not refer to the figure after reading the geometric elements (“ABC”) in the contextual part; in the second, they also did not refer to the figure after reading the old elements (“$\overline{AB}$” and “$\overline{BC}$”) in the following part; and in the third, the participants of both the groups referred to the figure when they read the new elements (“$\overline{DE}$”) in the following part. We tabulated the most likely and second most likely transition paths between IAs and found that the two versions of the nine-item transition paths all accorded with the pattern mentioned above.

Because the location of the new elements in the text differed in the two versions, the timing of referring from text to figure was also different. In Fig. 4, the group GN tended to finish reading the text before referring to the figure, whereas the group NGN often referred to the figure at the beginning of a sentence. When the group GN read the name of the new element (“$\overline{DE}$”), they already knew the location (on the “$\overline{AB}$” and “$\overline{BC}$”) and the role of the new element (“中點連線 ” meaning “the line segment connecting the midpoints of the two sides”); they could probably therefore imagine the spatial relation of $D$ (or $E$) and the triangle $ABC$. The group GN shifted their fixation from the text to the figure only to confirm their imagine. However, at the bottom of Fig. 4, the group NGN read the name of the new element “$\overline{DE}$” at the beginning of the following part, and they had no prior understanding of it. After they read the new element, their most likely subsequent IA transition skipped to point $D$ in the figure. In addition, when reading the three IAs “為,” “$\overline{AB}$,” and “$\overline{BC}$,” the participants regressed to inspect “$\overline{DE}$” again and again. The participants of the NGN version used the figure and other parts of the text to construct the spatial location and the role of “$\overline{DE}$.”

## Discussion

This study produced two main findings. The first was that the reading pattern for illustrated geometric descriptions was text-directed. Most adult readers looked first at the text, and then examined the corresponding elements in the figure. The second was that we confirmed the effects of given-new ordering on geometric texts. That is, although the description consistency with given-new ordering did not influence the accuracy of the question responses, the reaction time of question answer, fixation duration on figure segment, and number of saccades from text to figure were reduced. In addition, the timing of referring from text to figure differed between the GN version and NGN version.

An alternative explanation for why most readers first looked at the text segment on the left side of the material is that readers tend to first look at the *left* with respect to the *text*. In order to exclude this alternative explanation, we conducted an additional study. The materials were similar to those of the previous experiment, except that each description had the figure on the left and the text on the right. The participants comprised nine college students (mean age 24.6 years), and the total number of eye-tracking instances was 81. The outcome revealed that only in one instance (1.2%) did a participant look at the figure first. Among the remaining text-first cases, we observed that 70 instances (86.4%) were text-directed, while 10 instances (12.3%) where not. These results were almost similar to the previous finding. The additional results confirmed that the reading pattern for illustrated geometric descriptions was text-directed.

The text-directed reading pattern in the illustrated geometry description was consistent with the findings of numerous past studies in science articles (Hegarty, 1992; Hegarty, Carpenter & Just, 1991; Rayner et al., 2001; Schmidt-Weigand et al., 2010). Even though the participants spent nearly 40% fixation duration on geometric figures, they still read the text first. Moreover, the scanpath based on the Markov transition probability revealed that the timing of transferring to the figure was the reference to new geometric elements in the text. Such text-figure referencing pattern showed that readers used the text to construct initial spatial relations between the geometric elements and then used the figure to confirm the representation. One explanation for this is that the spatial relations demonstrated only by a geometric figure are insufficient to establish a definite meaning. For example, in Figs. 2, 3, and 4, point $D$ is located near the midpoint of $\overline{AB}$, but the participant has to read the text to understand the relationship between point $D$ and $\overline{AB}$. That is, the decoding of geometric figures depends on the message from other sources. Duval (1998) argues that in order to represent a mathematical object, a geometric figure must be anchored in a statement that fixes some properties represented by the visual image. Similarly, Andrá et al. (2015) advocated that graphs as objects do not exist as independent entities.

When using the accuracy of the question answer as a measurement, the word ordering of text did not affect comprehension, which is similar to the results of past studies (Chen & Wu, 2012; Tso et al., 2011; Yang, Lin & Wang, 2008). However, the reaction time for answering the question of the NGN version was longer than that of the GN version. If descriptions violated the given-new ordering, the participants were unable to locate a direct antecedent to incorporate the novel information into their existing memory structures when answering the questions. Thus, they had to create a bridging structure through inferences by alternating back and forth between the text and figure. These extra processes lead to the group NGN taking more reaction time to answer the questions.

In addition, this study showed that the text violating given-new ordering reduced the participants' reading efficiency. Even though the two versions differed in terms of text descriptions, the difference between their respective fixation durations was reflected in the figure segment. For the NGN version, because the new information preceded the relative description, the readers were unable to locate the new information referring to the given information. Rather, the readers needed to refer to the figure in order to search for corresponding information or increase the regression in text reading. As Hegarty and Just (1993) claim, the timing of interruptions in text reading and transitions to figure investigation is informative. When readers construct an initial mental model, figure-text integration moves from the local to the global level. The reader locates shared referents to integrate new information, thereby forming a complete mental model.

For the GN version, as the text describes the relationship of the given and the new information before representing the new elements, the readers were smoothly able to locate the new information with reference to the given information. Hence, the participants referred to the overall figure segment when encountering new geometric information at the end of the text. The readers of the GN version were soon able to build new information on the basis of given information to form more complete spatial images by reading the text. They usually inspected the figures to make sure that the spatial relation of geometric elements was in accord with the spatial image formed by reading the text.

Even though most participants' eye movements showed text-directed patterns, this did not imply that the figure was unimportant in the geometric reading. The participants of both the groups spent nearly 40% of fixation duration on the figures, which were higher ratios than those found for illustrated science texts (Hannus & Hyona, 1999; Rayner et al., 2001). That was probably because that geometric figure provided another representation and facilitated the readers' understanding. First, it requires strenuous effort to grasp and retain spatial information depending on text description alone. As indicated in Schnotz's (2005) theory, verbal and pictorial information are processed under different channels and representation principles. Although text expresses comparatively clear information, the textual description is presented sequentially. By contrast, figures could simultaneously present spatial relations and information from different geometric components, thereby reducing the cognitive load required to form propositional representations. Second, although the readers can image the configuration through text reading, they may also examine figures to verify their imagination (Hegarty & Just, 1993). Third, geometric reasoning operates as a discursive process embedding a purely figural process (Gal & Linchevski, 2010), although visualization does not always help reasoning (Duval, 1998). Based on visual comparison of the size of angles, areas, or the length of lines, we can form simple reasoning or computation.

## Further Research and Implications

The following recommendations are provided for future research as well as educational implications based on the characteristics of the reader, reading material, and task demand. First, the population of participants needs to be expanded. In the present study, the participants were still college students, as in the case of previous research in which authors claim that the reading pattern of illustrated text is text-directed (Hegarty, 1992; Hegarty & Just, 1993; Rayner et al., 2001; Schmidt-Weigand et al., 2010). For secondary school students whose reading fluency is weaker than that of college students, how they read the illustrated geometric texts is an educational issue.

Second, the different materials and tasks needs to be examined. In this study, we used the illustrated description, which do not pose a question, and reading task and found that most readers showed a text-first pattern. If the material is complete text, or demand of the task is to memorize, solve problem, or proof, what is the pattern of the scanpath?

Third, from an illustrated geometric text, we observed several text-first subpatterns that differed from the pattern ascertained by Hegarty and Just (1993). This may be due to differences in the domain of the topics and the representation of materials. The illustrated text used in Hegarty and Just's study was about pulleys and their operation, and words were the major representation; in our study, however, the illustrated text was about geometry and employed many numbers and symbols. Thus, the reading patterns of different domains and the representation types of reading materials need to be examined.

Fourth, the degree and means by which a description's consistency with given-new ordering may influence students' question comprehension requires further investigation. This study found that geometric descriptions violating given-new ordering prolonged reaction time and figure-fixation duration but did not influence the accuracy of answers. However, in situations in which students are under severe time constraints (e.g. an exam), geometry questions with more complicated structures or a greater quantity of information may lead to an increase in cognitive load and cause greater interference for readers.

The majority of illustrated geometry questions in Taiwanese textbooks are not consistent with given-new ordering. This study' results showed that descriptions violating given-new ordering reduced readers' reading efficiency. If it is necessary for a geometric description to first present new information, then additional reading time should be allocated to students, and additional guidance should be given on the integration of figure-text information.

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