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The function of diagram with numbered arrows and text in helping readers construct kinematic representations: Evidenced from eye movements and reading tests

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ABSTRACT

Eye-tracking technology can reflect readers' sophisticated cognitive processes and explain the psychological meanings of reading to some extent. This study investigated the function of diagrams with numbered arrows and illustrated text in conveying the kinematic information of machine operation by recording readers' eye movements and reading tests. Participants read two diagrams depicting how a flushing system works with or without numbered arrows. Then, they read an illustrated text describing the system. The results showed the arrow group significantly outperformed the non-arrow group on the step-by-step test after reading the diagrams, but this discrepancy was reduced after reading the illustrated text. Also, the arrow group outperformed the non-arrow group on the troubleshooting test measuring problem solving. Eye movement data showed the arrow group spent less time reading the diagram and text which conveyed less complicated concept than the non-arrow group, but both groups allocated considerable cognitive resources on complicated diagram and sentences. Overall, this study found learners were able to construct less complex kinematic representation after reading static diagrams with numbered arrows, whereas constructing a more complex kinematic representation needed text information. Another interesting finding was kinematic information conveyed via diagrams is independent of that via text on some areas.

1. Introduction

Words and diagrams are the two major media often used to communicate scientific knowledge or know-how. Both are typically used in illustrating mechanical kinematics, which are fundamental to comprehending how a machine works. (Hegarty, Kriz, & Cate, 2003; Heiser & Tversky, 2006; Mayer & Gallini, 1990). In general, the diagram has the advantage of depicting the configuration of components of a mechanical system; text has the advantage of describing its kinematics, such as how the components affect each other's movements and what principle caused these movements (Larkin & Simon, 1987; Mayer, 1989). However, within many science textbooks and other scientific publications, such as manuals and popular science essays, diagrams with arrows are frequently relied on by designers of teaching materials to depict mechanical kinematics to some degree.

Although there have been some pioneering research studies that thoroughly examined the process of integrating text and diagrammatic information while reading a mechanical illustrated text (Hegarty, 1992; Hegarty & Just, 1993; Johnson & Mayer, 2012; Mason, Tornatora, & Pluchino, 2013), or that have investigated which form of media (e.g., text, diagram, animation) most effectively conveyed mechanical kinematic representation (Boucheix & Lowe, 2010; Hegarty et al., 2003; Kriz & Hegarty, 2007), no research has yet investigated the specific functions of diagrams with numbered arrows versus text in conveying mechanical kinematics.

The process approach offered by combining eye-tracking methodology with computer recording is a methodological breakthrough in psychological research. It allows psychologists to investigate the cognitive processes of reading and, thus, tackle research questions that traditional methods (e.g., reading tests, thinking-aloud protocol) could not. The eye-mind assumption (Just & Carpenter, 1980) proposes that, when visual information is read or viewed, the relevant information is processed in the readers'

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mind. Accordingly, eye-tracking technology objectively and instantaneously measures the reading process (Rayner, 1998). An advantage of eye-tracking methodology is that participant eye movement can be simultaneously tracked and transferred to the experimenter's computer. This lets the experimenter know if the participant is reading the text seriously. Eye-tracking methodology is receiving increased attention in educational research about multimedia learning (Hegarty & Just, 1993; Jian, 2016; Jian & Wu, 2015; Johnson & Mayer, 2012; Kriz & Hegarty, 2007). Therefore, this study investigated the function of diagrams with numbered arrows and illustrated text individually in conveying kinematic information of how a machine works by recording learners' eye movements and conducting comprehension tests, and argued whether numbered diagrams can support comprehension of simple processes, but descriptive text is necessary to adequately convey information for more complex processes.

1.1. Reading research of mechanical kinematic representation

1.1.1. The research used comprehension tests

In early research on this topic, investigators used comprehension tests (e.g., retention tests and transfer tests) that measured learning outcomes to investigate which diagram design information was helpful for learners to construct a good mechanical kinematic representation. For example, Mayer and Gallini (1990) investigated the effects of prior knowledge and diagram design on the comprehension of how a mechanical system works. Undergraduate participants with different degrees of mechanical knowledge were asked to read an illustrated text that described how car brakes work. This illustrated text was manipulated with regard to the parts and steps of the car brake on the diagram: a diagram with only labels that indicated the parts, a diagram with arrows and sentences description that indicated the steps, or a diagram with both parts and steps. The participants with low mechanical knowledge who read the parts-and-steps diagrams outperformed the participants of other two groups on a retention test and a transfer test. However, this discrepancy was not observed for the participants with high mechanical knowledge. Although, at that time, the researchers did not directly propose the term *kinematic representation* to indicate the concept of dynamic information (Mayer & Gallini, 1990), the use of the term *steps* implied this concept.

In recent years, Hegarty et al. (2003) investigated the role of mental animation and external representation in understanding a mechanical system. Undergraduate participants were asked to learn how a flushing cistern works. The flushing cistern described the “outlet process” and “inlet process” of the flushing cistern. The outlet process flushes water out of the tank and into the bowl of the flushing cistern. The inlet process pumps fresh water into the flushing cistern tank from the water inlet pipe. Students learned how a mechanical system works from various instructional treatments including a diagram of the system, three different status diagrams of the system, a computer animation simulating how the system works, and an animation accompanied by verbal commentaries. The result of their study showed learners were able to construct a configure representation but were unable to construct a kinematic representation by reading a single diagram. However, when reading the three diagrams, participants were able to actively infer the movements of the system components one-by-one and comprehended the casual relations of events, as well as understand the configuration and predict how the system worked. Besides, they found there was no evidence that animated diagrams led to superior understanding of dynamic processes compared to static diagrams.

1.1.2. The research used comprehension tests and eye-tracking technology

At approximately the same time with Mayer and Gallini (1990) only used comprehension tests to executing kinematic reading research, Hegarty and colleagues (Hegarty & Just, 1993) started to utilize comprehension tests and eye-tracking technology jointly to investigate the cognitive processes of constructing kinematic representations of a mechanical system while reading an illustrated text, as well as what factors influenced learning outcomes.

For example, Hegarty and Just (1993) carefully examined the process by which learners with different prior knowledge coordinated diagrammatic and text information to incrementally construct a kinematic representation of a pulley system. Undergraduate participants with a high or low level of mechanical knowledge were randomly assigned into one of the three groups: diagram alone, text alone, or both diagram and text. The low-knowledge readers found the construction of a mental model to be more difficult than the high-knowledge readers did. Furthermore, low-knowledge readers had lower scores on the comprehension tests, made significantly more saccades between the diagram and the text, and spent more reading time dealing with the local information in the diagram.

Kriz and Hegarty (2007) used reading comprehension tests and eye-movement technology to examine the effects of arrows showed an animation introducing how a flushing system works. The reading material this research used was similar to that of Hegarty et al. (2003) which we mentioned previously. University participants viewed either the interactive animation with arrows or the interactive animation without arrows. The scoring criterion was also the same as Hegarty et al.'s (2003) including each step of the flushing system works, and could be categorized into the inlet-processing and outlet-processing system. The results of eye movement data revealed that participants receiving the animation with arrows spent a significantly greater proportion of time in the arrow regions and the space that incorporated both the parts and arrows than the participants who saw the animation without arrows. However, both groups had similar comprehension test scores. Besides, the results also revealed that comprehension of some steps was considerably less accurate (for those steps describing difficult kinematic relations like outlet processes) than that of other steps (for those steps describing simple kinematic relations like inlet processes).

Together, previous studies have provided a preliminary understanding of the effect of multiple representations of learning kinematics concept (Hegarty et al., 2003; Mayer & Anderson, 1992), and of the cognitive process of constructing kinematic representations of a mechanical system while reading an illustrated text (Hegarty & Just, 1993) or reading an animation (Kriz & Hegarty, 2007). However, there were some research limitations and controversial issue as yet unsolved.

1.2. Limitations of previous research

First, the facilitation effect of arrows on learning kinematic concepts was not clear. Kriz and Hegarty (2007) revealed that arrows presented on an animation conveying how a flushing system works only had a visual attention attraction effect (evidenced from the fact that readers who viewed arrows on the animation spent more reading time on the arrows and its near areas, as measured by eye fixations, than did the readers who viewed the same animation without arrows), but had no cognitive comprehension effect (evident from the lack of difference in the comprehension test performances of the arrow and non-arrow groups). However, some studies showed that arrows had a facilitation effect on kinematics reading comprehension (Jian, Wu, & Su, 2014; Hegarty et al., 2003;