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Learners' eye movements during construction of mechanical kinematic representations from static diagrams

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A B S T R A C T

We investigated the influence of numbered arrows on construction of mechanical kinematic representations by using static diagrams. Undergraduate participants viewed a two-stage diagram depicting a flushing cistern (with or without numbered arrows) and answered questions about its function, step-by-step. The arrow group demonstrated greater overall accuracy and made fewer errors on the measure of continuous relations than did the non-arrow group. The arrow group also spent more time looking at components relevant to the operational sequence and had longer first-pass fixation times and shorter saccade lengths. The non-arrow group made more saccades between the two diagrams. Analysis of transition probabilities indicated that both groups viewed components according to their continuous relations. The arrow group followed the numbered arrows whereas the unique pathway of the non-arrow group was to compare the two diagrams. These findings indicate that numbered arrows provide perceptual information but also facilitate cognitive processing.

1. Introduction

The study of inner kinematic representation is important and unique in cognitive psychology; it is concerned with high-level cognitive behavior, specifically with how people animate outside events inside the human mind. Inner kinematic representation is defined as a coherent mental model that learners construct over time from external representations through cognitive activities (Ainsworth & VanLabeke, 2004; Hegarty, Narayanan, & Freitas, 2002); it involves combining temporal and spatial information of an external event. However, how and when this occurs has been unclear.

In many learning topics involving kinematic representation, the mechanical system is closely linked to daily life, for example, a bicycle, a flush cistern, or a washing machine. Readers often learn how a mechanical system works for practical purposes without formal instruction, for example, without learning to use or repair a system by reading manuals, textbooks, or popular science essays. These essays usually use diagrams to depict the configuration of the mechanical system, and it is clear that diagrams can convey configuration information to readers (Hegarty & Just, 1993; Heiser & Tversky, 2006; Mayer, 1989). In addition to configuration properties, kinematic properties are necessary for readers to be able to form a good mechanical mental model (Boucheix & Lowe, 2010; Hegarty, 1992; Mayer & Gallini, 1990). However, the role of kinematic properties is seldom noticed when reading static diagrams.

1.1. Using eye-tracking technology to investigate kinematic representation formation

In the last 20 years, several studies have used eye-tracking technology to investigate the effects and processes involved in kinematic representation formation from reading diagrams or articles with diagrams. For example, Hegarty (1992) asked undergraduate participants to read a pulley-system diagram with two sentences, and investigated how readers constructed the kinematic representation of the pulley system while imagining how it operates. Hegarty (1992) described participants' eye movements, and used Kintsch and Van Dijk's (1978) reading theory to explain the processes involved in imagining how a pulley system operates from reading a diagram. The results showed that participants would fixate on several relevant and continuous pulley components in the diagram, and eye fixations moved back and forth between the diagram and sentences. Readers also re-fixated on the

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components of the pulley diagram. These results indicate that participants were unable to simulate and process all the detailed information involved in pulley system operation at the same time. Instead, these simulations and processes were processed in a step-by-step manner. It was essential for readers to decode each part of the pulley system first, and then generate a representation. "Mental animation" is first described in this study (Hegarty, 1992) to refer to inference processes. This concept has continued to be used in the research on kinematic representation (Hegarty, Kriz, & Cate, 2003; Kühl, Scheiter, Gerjets, & Edelmann, 2011).

According to the theoretical models proposed by Mayer (2005), a well-designed signaling is helpful to readers. Visual cueing in the form of static picture, has been investigated in several studies (Mason, Pluchino, Tornatora, & Ariasi, 2013; Mason, Tornatora, & Pluchino, 2013; Mautone & Mayer, 2007). However, for one type of visual cueing, arrows, previous studies showed that arrows did not facilitate kinematic learning when they were shown on an animation. For example, Kriz and Hegarty (2007) utilized paper-and-pencil tests and eye tracking to study the processes involved in forming a mechanical kinematic representation while reading an animation. Two groups of undergraduate students viewed an animation of a flushing cistern with or without arrows (arrow group versus non-arrow group). Eight arrows appeared on the screen, one at a time, to indicate a part's direction of movement and to signal each important step in flushing cistern operation. For example, arrows sequentially appeared below three components: (1) *the "handle" is pushed,* (2) *the "connecting rod" pulls the "lower disk" up, and* (3) *the lower disk pushes the "upper disk" forward.* Results showed that the arrow group spent more reading time on the arrow locations surrounding areas than did the non-arrow group, but the two groups did not differ on comprehension test scores. That is, there was a dissociation between the results based on eye movements and the comprehension test. Kriz and Hegarty (2007) found that both arrow and non-arrow groups made many errors in their construction of kinematic representations of the flushing cistern. These researchers attributed this unexpected phenomenon to the fact that the arrows only attracted perceptual attention to the important areas on the animation, and that this was not sufficient to promote the construction of the correct mechanical mental model.

Boucheix and Lowe (2010) also measured readers' eye movements to study how visual cues on an animation influence kinematic representation formation. Undergraduate students viewed an animation depicting how the inner components of a piano move when a piano key is pressed. Three signaling types were manipulated: arrows with spreading colors, arrows, and no arrows. Learners who read arrows with spreading colors in the animation spent more reading time looking at the relevant components of the piano compared to the other two groups when the relevant features were highlighted both spatially and temporally. In addition, learners who read arrows with spreading colors had better performance (compared to the arrow and non-arrow groups) on a comprehension test involving low-salience and highly-relevant features. These results indicate that visual signals are helpful for guiding learners' attention. Arrows with spreading color are an efficient way of providing visual continuity, which facilitates construction of a good kinematic representation. However, the arrow group did not perform better on the comprehension test than did the non-arrow group. These findings are similar to those of Kriz and Hegarty (2007). Together, these studies imply that using arrows as visual cues benefits perceptual extraction of the visual features of a display, but does not produce cognitive benefits (e.g., facilitating encoding of the displayed information and constructing a good mental model of the referent).

We propose an alternative explanation for the unexpected results in these studies (Boucheix & Lowe, 2010; Kriz & Hegarty, 2007). We suggest that, when viewing the animation, it may be too difficult for low-knowledge readers to keep all of the transiently displayed information in memory. This claim is supported by the fact that the comprehension tests showed floor effects thus indicating that participants did not construct a kinematic representation.

1.2. Properties of a mechanical kinematic representation

Although considerable research has addressed the importance of dynamic information in forming a mechanical kinematic representation (Boucheix & Lowe, 2010; Hegarty, 1992; Heiser & Tversky, 2006; Kriz & Hegarty, 2007), there are few studies concerned with whether dynamic and static information have different properties, and whether these properties play different roles in understanding a mechanical operation. Based on a review of previous literature, we propose that a mechanical kinematic representation has three properties: order relations, direction alteration, and continuous relations. To illustrate these properties we use the following example describing how a flushing cistern works:

> "*The handle pulls the connecting rod up, then the connecting rod pulls the lower disk up, the lower disk pushes the upper disk up, and then the upper disk pushes water flushes into the siphon pipe.*"

To construct an inner kinematic representation of the above sentence three properties are incorporated. The order relation of the representation is "*Push the handle of a flushing cistern, and then water flushes into the siphon pipe.*" This is because, when a mechanical system operates, a component of the machine will first activate another component and then a dynamic event will occur, resulting in an end state (Boucheix & Lowe, 2010; Kriz & Hegarty, 2007). This order relation omits the middle processes, only has an early-or-late sequence, and does not describe the connective/continuous component relations of the flushing cistern. Early-or-late sequences are an essential part of order-relation properties and detailed continuity is unnecessary. The order-relation property is therefore a global temporal representation. The second property, direction alteration, represents the sentence as, "*The connecting rod pulls the lower disk up.*" In this case, altering the directions of mechanical components produces dynamic operations. The direction-alteration property is a global spatial representation (Hegarty, 1992; Hegarty & Just, 1993). The third property, continuous relation, represents the sentence as, "*The handle pulls the connecting rod up, then the connecting rod pulls the lower disk up, and the lower disk pushes the upper disk up,*" thus describing three continuous relations between components of the flushing cistern operation. The continuous-relation property encompasses sequence and continuity relationships between the components of a mechanical system (Boucheix & Lowe, 2010; Hegarty, 1992; Heiser & Tversky, 2006); it is a local temporal and spatial representation.

1.3. The present study and hypotheses

The present study investigated how learners construct kinematic representations of a mechanical system by reading static diagrams. Learners were presented with a two-stage diagram depicting a flushing cistern with or without numbered arrows (arrow group versus non-arrow group) and then completed a test about how the system works step-by-step. There were two research purposes. The first was to investigate if arrows on diagrams serve only a perceptual function or whether they may also benefit cognitive processing. The second purpose was to investigate whether providing visual cues with numbered arrows on diagrams would influence which properties were used to form the