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

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ABSTRACT

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 mechanical kinematic representation; we also examined the cognitive processes involved in kinematic mental model construction.

The differences between this study and previous signaling studies (e.g., Boucheix & Lowe, 2010; Kriz & Hegarty, 2007) were that the diagrams were static in this study and the arrows in this study were numbered, whereas their studies used animations and arrows were not numbered. The numbers provide an explicit representation of the causal ordering of events. In contrast in the Kriz and Hegarty (2007) study the arrows just appeared (and disappeared) sequentially, providing only an implicit representation of ordering.

To investigate whether arrows serve a perceptual or a perceptual/cognitive purpose we formed two hypotheses. First, we expected that an arrow group would outperform a non-arrow group on a step-by-step question about function of the cistern (Hypothesis 1a). This hypothesis is supported by previous research indicating that arrows can convey dynamic information such as indicating sequential operation or directions altered (Heiser & Tversky, 2006; Kriz & Hegarty, 2007; Mayer & Gallini, 1990). We also hypothesized that eye movement patterns would reveal that an arrow group would spend more time (compared to a non-arrow group) viewing the components indicated (by arrows) as relevant to the operational sequence and would ignore "irrelevant" components not indicated by arrows (Hypothesis 1b).

To investigate which properties of mechanical kinematics had the effect of arrows for forming a kinematic representation and to investigate links to cognition, we formed two hypotheses. First, we hypothesized that numbered arrows on the diagrams would mainly affect the continuous-relation property of kinematic representation formation because this property is a more refined characteristic (Boucheix & Lowe, 2010; Hegarty, 1992; Heiser & Tversky, 2006) and is difficult to construct. We expected that numbered arrows would assist learners in mastering the continuous relationships between components as they change over time and in forming a better mechanical kinematic representation. We also expected to see the arrow group outperform the non-arrow group in grasping the continuous relation measured by a step-by-step question (Hypothesis 2a). However, we made no hypotheses concerning the order-relation and direction-alteration properties of the kinematic representation. To test the cognitive processes involved in kinematic mental model construction, we expected that eye tracking measures would reveal different reading paths (and therefore different strategies) for arrow and non-arrow groups. In particular, numbered arrows were expected to guide learners' visual attention in the early stages of reading. We therefore expected that the arrow group would follow the numbered arrows at the initial processing stage and then switch their eye fixations more often between connected components in which arrows indicated start and end locations. We expected that eye movements of the non-arrow group would indicate that they were reading components that were located near one another or were comparing the status of the same components in the two-stage diagrams (Hypothesis 2b).

2. Method

2.1. Participants

Forty-six undergraduate students (12 males and 34 females) from the National Taiwan Normal University volunteered to participate for a small monetary reward (200 New Taiwanese Dollars, equal to 5 Euros). The mean age of participants was 23.05 years ($SD = 3.08$) and they were students in education, management, arts, or social science. We excluded students who majored in science or engineering and as such, participants were expected to have minimal background knowledge in these areas. All participants had normal or corrected-to-normal vision.

2.2. Materials

Experimental materials were two diagrams (Hegarty et al., 2003) describing how a flushing cistern works. This mechanical system is often used to flush toilets, but the working principle of this flushing cistern is different from typical Taiwan toilets, so we assumed that the participants in this study had not previously seen or physically repaired this particular mechanical system.

The two diagrams, respectively 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. Our study manipulated whether numbered arrows (in red) were presented on the two diagrams (Fig. 1). The arrows were numbered (1–4 for outlet process; 5–8 for inlet process) to indicate each sequential step of flushing cistern operation. Except for the presence or absence of numbered arrows, there were no differences in the content and arrangement of the two versions (arrow and non-arrow).

To get the largest possible area for analyzing participants' eye movements, we arranged the outlet-process diagram on the upper-left section and the inlet-process diagram on the lower-right section of the screen. The diagrams were displayed on a single screen, and there was no scroll bar nor continued pages. Before reading the two diagrams about how a flushing cistern operates, all participants were presented with labels for the 10 mechanical components of the decoding-structure flushing cistern (Fig. 2). Participants were asked to remember all the labels and shapes of flushing cistern components presented on the screen. However, in the subsequent reading procedure, the component names were not shown on the diagrams (i.e., the diagrams were unlabeled).

Such a design was used because any information (e.g., color, label, word, and picture) on the screen may attract readers' attention, which would make it difficult to distinguish which factor was causing readers' behavior when analyzing the eye-movement data. The participants needed to use the labels to describe components on the step-by-step question after reading the diagram. It was therefore important that participants remember the labels.

The step-by-step question was translated from Hegarty et al. (2003) into Chinese. Participants were asked to imagine how the flushing cistern operates when the handle is pushed, and to write down each step and the components involved as clearly as possible. Participants were also encouraged to write down the operational principles of the system.

2.3. Apparatus

Participants' eye movements were recorded using an Eyelink 1000 at a sampling rate of 1000 Hz. A chin bar was used to minimize head movement. Viewing was binocular and eye movements were recorded from the right eye only. Diagrams were presented on a 24-inch LCD monitor with a resolution of 1920×1200 pixels. The two flushing cistern diagrams were the same size on the screen, each measuring approximately 26 cm $\times$ 17 cm (962×629 pixels). The distance between the monitor and participants was 60 cm. The reading material covered 46° (horizontal) $\times$ 30° (vertical) of visual angle on the screen.

2.4. Procedure

Half of the participants were randomly assigned to read the diagrams with numbered arrows (arrow group), and half were

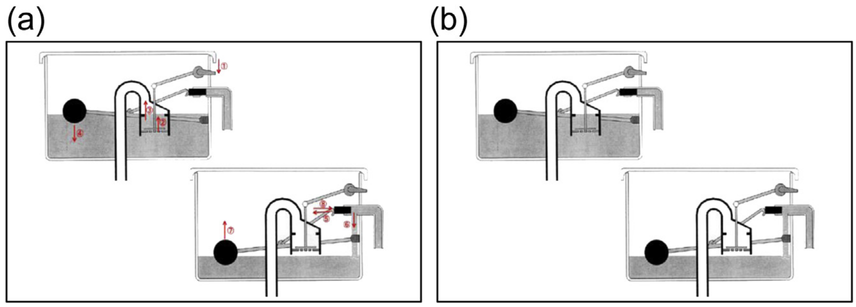

Fig. 1. The two-stage diagrams of a flushing cistern viewed by the arrow and non-arrow groups. (a) illustrates the arrow version and (b) illustrates the non-arrow version.

assigned to read the diagrams without numbered arrows (non-arrow group). Prior to the learning phase, all participants studied the 10 flushing cistern component labels for 2 min. Then the formal learning phase began. A 12-point calibration and validation of eye-movements was conducted for each participant. Participants were then instructed to keep their head still throughout the reading procedure. The two flushing cistern diagrams were shown on the screen, and participants were instructed to spend approximately 5 min reading the diagrams to learn how the flushing cistern operates; participants were then given 9 min to complete the step-by-step question. Participants were told that the upper-left diagram was the first flushing stage and that the lower-right diagram was the second stage. Once participants finished reading the diagrams, they could press a key on the keyboard to finish the reading stage and start the step-by-step question; if they did not press a key, the diagrams automatically disappeared after 5 min. The time limit for each phase (labels, reading, and step-by-step question) was based on research by Hegarty and colleagues (Hegarty et al., 2003; Kriz & Hegarty, 2007), and we performed a pilot study to confirm that the limited times were sufficient for readers to complete all phases of the study. The experimental session lasted for approximately 20–30 min.

2.5. Data selection and scoring criterion

Eye-movement data from six participants were discarded due to apparent drift. Therefore, data from 40 participants (20 from the arrow group, and 20 from the non-arrow group) were included in the analyses. In addition, as in previous eye-movement studies (Andrews, Miller & Rayner, 2004; Jian, Chen & Ko, 2013; Jian & Wu, 2012), any fixation shorter than 100 ms was excluded, which in this case was approximately 3% of fixations.

Several eye-movement indicators were selected according to previous studies of diagram reading or reading articles with diagrams; each of them reflect different types of cognitive processing (Grant & Spivey, 2003; Hannus & Hyönä, 1999; Hegarty, 1992; Hegarty, Canham, & Fabrikant, 2010; Henderson, Weeks, & Hollingworth, 1999; Jian, 2012; Jian & Wu, 2012; Johnson & Mayer, 2012; Mason et al., 2013; Rayner, Rotello, Stewart, Keir, & Duffy, 2001). Therefore, several measures were included in the analyses.

The first measure was total reading time (the sum of all fixation durations on an area of interest), which provides an indication of the overall difficulty and the degree of cognitive effort required to process the reading materials. The second measure was mean saccade length (the average length of saccades made on the diagram). Some studies (Jian, 2012; Jian & Wu, 2012; Kriz & Hegarty, 2007) have used this indicator to reflect the degree of attentional guidance toward visually presented information. If readers' attention can be guided by the visual information (e.g., arrows, color) on the diagram, fixations should be located on the areas near to this obvious visual information with more focus, therefore shortening mean saccade length. The third measure was the number of saccades between the two diagrams (the number of times the participant moves eye fixation from one diagram to another diagram or vice versa), which reflects inference and integration of

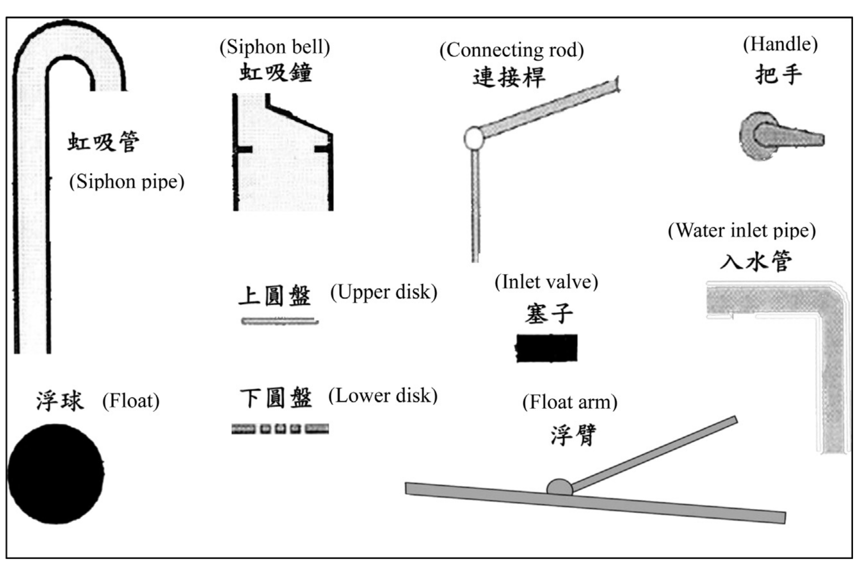

Fig. 2. The flushing cistern component labels and shapes and the decoding-structure for flushing cistern function.

information between the two diagrams. The fourth measure was the proportion of fixation duration (the fixation duration on specific target regions divided by the total fixation duration during the learning episode), which reflects selective attentional focus on specific target regions during learning. The fifth measure was first-pass fixation time (the sum of all fixation durations on a target region before exiting it), which reflects the initial and more automatic processing of diagram features. For example, in the scene perception literature, first-pass measures are often thought to reflect object encoding (Henderson et al., 1999). The sixth measure was second-pass fixation time or look-back fixation time (the sum of all fixation durations that return to a target region after its first-pass reading), which reflects higher order cognitive and intentional processing during reading. For example, comprehension (Rayner, 1998) or integration (Mason et al., 2013).

In addition to the above six eye-movement indicators, we wondered whether the sequence of eye fixations could be analyzed to investigate the reading strategies that participants adopted. A series of matrix calculations were carried out to analyze the sequence of eye fixations. This statistical method is frequently used to investigate how behavior is sequenced moment to moment (Bakeman & Gottman, 1997).

The accuracy of participants' mental models was evaluated based on the steps mentioned in the step-by-step reports. We compiled a list of 20 steps in the causal chain of events that occur when the handle of a flushing cistern is pushed. Of these steps, steps 1–10 were outlet processes, and steps 11–20 were inlet processes. These steps were based on the study by Kriz and Hegarty (2007) who provided an overview of flushing cistern operation. We then invited a mechanics professor to confirm that these steps completely describe flushing cistern operation, and set the 20 steps as scoring criteria.

For scoring, we invited a graduate student who majored in mechanics to score participants' written reports according to the scoring criteria. First, the rater needed to divide participants' reports into sentences according to the scoring criteria steps, and then judge whether each description conveyed the appropriate step or not. Misspelled words were credited as correct answers if the meaning of these words were identified as being close to the correct terms. For example, a participant could write "虹吸鐘/siphon bell" as "虹吸槽/siphon trough." However, if participants' answers were incorrect, the error was classified into one of three error types that correspond to the previously mentioned properties of mechanical kinematic representations: (1) order relation errors (e.g., if the sequence of events is written as "13, 3, 19," step 3 would be an error because it should occur before step 13); (2) direction alteration errors (e.g., writing "the connecting rod pulls the lower disk *down*," when the correct answer is "pulls *up*"); and (3) continuous relation errors (e.g., writing "Component A connects Component B," when the correct answer is "Component A connects Component C").

3. Results

3.1. Learning outcomes

The two dependent measures of learning outcome were accuracy and error type on the step-by-step question. These results are shown in Table 1. The arrow group had significantly higher accuracy on total steps, outlet-process steps, and inlet-process steps than the non-arrow group, $t(38) = 5.90$, $p < .001$, $d = 1.85$; $t(38) = 4.44$, $p < .001$, $d = 1.44$; $t(38) = 4.95$, $p < .001$, $d = 1.58$. However, the arrow group had significantly fewer continuous relation errors than did the non-arrow group, $t(38) = -2.08$, $p < .05$, $d = -0.66$, and the two groups did not differ significantly on the number of order relation errors or direction alteration errors, $ps > .10$. Additionally, the groups did not differ significantly in response time for completing the step-by-step question, $p > .10$.

Table 1
Accuracy and error type on the step-by-step question for arrow and non-arrow groups.

	Arrow group		Non-arrow group		*t*-value
	M	(*SD*)	*M*	(*SD*)	
Accuracy (%)					
Outlet-process steps	21	(10)	8	(8)	4.44***
Inlet-process steps	62	(20)	28	(23)	4.95***
Total steps	42	(13)	18	(13)	5.90***
Error type					
Order relation	0.10	(0.31)	0.10	(0.31)	0.00
Direction alter	0.20	(0.52)	0.10	(0.31)	0.74
Continuous relation	0.60	(0.94)	1.35	(1.31)	−2.08*
All error types	0.90	(1.15)	1.55	(1.28)	−1.53
Response time (minute)	6.25	(1.79)	6.60	(2.14)	−0.56

*$p < .05$, ***$p < .001$.

3.2. Eye movement analysis

There were three levels of analysis ranging from a larger to smaller area of the diagram. The first level included the whole diagram as an analysis unit, the second level analyzed the two diagrams separately, and the third level analyzed the individual flushing cistern components. In addition, we analyzed the sequence of eye fixations in order to illustrate participants' reading pathways.

3.2.1. Analyses of the whole diagram

The two dependent measures for the whole diagram analyses were total reading time and mean saccade length. Means and standard deviations for these eye-movement analyses are presented in the upper portion of Table 2. There were no significant group (arrow versus non-arrow) differences in total reading time, $p > .10$. However, the arrow group had significantly shorter mean saccade length than the non-arrow group, $t(38) = -3.61$, $p < .001$, $d = -1.26$.

3.2.2. Analyses of the two diagrams

The six dependent measures for analyses of the two diagrams were total reading time, proportion of fixation duration on the diagram, first-pass fixation time, second-pass fixation time, mean saccade lengths, and the number of saccades between the two diagrams. Means and standard deviations for these eye-movement analyses are presented in the middle and lower portions of Table 2. The arrow group had significantly longer first-pass fixation time than the non-arrow group for both the outlet-system diagram, $t(38) = 2.68$, $p < .05$, $d = .85$ and the inlet-system diagram, $t(38) = 2.35$, $p < .05$, $d = .75$. However, the non-arrow group made more saccades between the two diagrams than did the arrow group, $t(38) = -2.08$, $p < .05$, $d = -.66$. The groups did not differ significantly in total reading time, proportion of fixation duration on the diagram, second-pass fixation time, or mean saccade length for either process diagram, $ps > .10$.

These results show that the arrow group and non-arrow group did not differ in performance in terms of total reading time for either the whole diagram or the separate two diagrams. This suggests that reading time was not the main factor driving differences in learning outcomes between the two groups. Therefore, to further investigate processes and strategies during construction of a kinematic representation, we conducted an analysis of eye movements related to the detailed components of the flushing cistern.

Table 2
Means and standard deviations for eye-movement measures for arrow and non-arrow groups on whole diagram and two stage diagram measures.

	Arrow group		Non-arrow group		*t*-value
	M	(*SD*)	*M*	(*SD*)	
The whole diagram					
Total reading time (s)	181.82	(89.19)	158.73	(81.10)	0.92
Mean saccade length (visual angle)	2.92	(0.49)	3.69	(0.71)	−3.61***
The two-stage diagrams					
Outlet-process diagram					
Total reading time (s)	81.52	(38.23)	74.99	(43.81)	0.50
Proportion of fixations on diagram	0.56	(0.13)	0.57	(0.11)	−0.22
First-pass fixation time (s)	15.36	(9.70)	6.64	(10.80)	2.68*
Second-pass fixation time (s)	66.16	(37.29)	68.35	(46.73)	−1.64
Mean saccade length (visual angle)	2.92	(0.48)	3.14	(0.47)	−1.46
The number of saccades from inlet to outlet	15.55	(9.40)	23.70	(14.73)	−2.09*
Inlet-process diagram					
Total reading time (s)	67.49	(43.00)	59.14	(38.47)	0.65
Proportion of fixations on diagram	0.44	(0.13)	0.43	(0.11)	0.24
First-pass fixation time (s)	2.21	(2.41)	0.88	(0.73)	2.35*
Second-pass fixation time (s)	65.28	(43.50)	58.26	(38.65)	0.54
Mean saccade length (visual angle)	3.20	(0.39)	3.31	(0.51)	−0.76
The number of saccades from outlet to inlet	14.90	(9.39)	24.00	(15.70)	−2.23*

*$p < .05$, ***$p < .001$.

3.2.3. Analyses of the detailed components of the flushing cistern

We classified five components (with or without arrows) on the outlet or inlet diagrams as areas of interest. These analyses were concerned with how readers allocated attention to different components, and in particular whether the arrow manipulation affected temporal or spatial attention distribution.

The five areas of interest on the outlet and inlet diagrams (for the arrow diagram) are shown in Fig. 3. They were: (1) handle and arrow 1 versus handle, (2) siphon bell, arrow 2 and arrow 3 versus siphon bell, (3) float and arrow 4 versus float and arrow 7, (4) inlet valve versus inlet valve, arrow 5 and arrow 8, and (5) water inlet pipe versus water inlet pipe and arrow 6. The float arm on the diagram was not selected as an area of interest due to being partly covered by the siphon bell. In addition, we included arrow 2 and arrow 3 in the siphon bell in the same area of interest, and arrow 5 and arrow 8 in the inlet valve in the same area of interest because the distance between the two arrows was too small to be covered by separate fixations. The non-arrow diagram edition contained no arrows on the regions of interest in either diagram, but it is important to note that the locations and regions of interest were the same as for the arrow diagrams.

We conducted two-way ANOVAs to test the main effects of Arrow (arrow group versus non-arrow group) and Diagram (outlet-process diagram versus inlet-process diagram), and the interaction between these two variables. Means and standard deviations for the proportion of fixation duration for both groups are presented in Table 3.

For the *handle* area of interest, there was no main effect of Arrow, $p > .10$, but there was a significant main effect of Diagram, $F(1, 38) = 49.97$, $p < .001$, $\eta^2 = .57$; the interaction between Arrow and Diagram was also significant, $F(1, 38) = 7.12$, $p < .05$, $\eta^2 = .16$. Simple main effects showed that the proportion of fixation duration on the

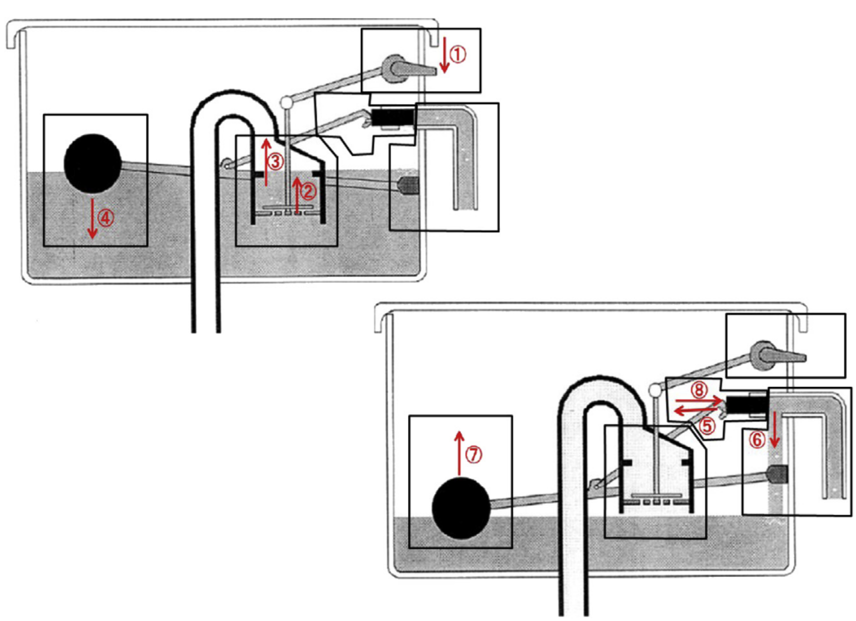

Fig. 3. Areas of interest for eye-movement measures of detailed components of the two-stage diagrams (with and without arrows).

Table 3
Means and standard deviations of the proportion of fixation durations for arrow and non-arrow groups analyzed according to the components of the flushing cistern diagram.

Interest areas (%)	Arrow group		Non-arrow group	
	M	(*SD*)	*M*	(*SD*)
Outlet diagram				
Handle + arrow 1	4.30	(2.30)	2.71	(2.50)
Siphon bell + arrow 2, 3	24.28	(8.30)	19.67	(7.25)
Float + arrow 4	4.79	(2.41)	2.74	(2.00)
Inlet valve	3.49	(2.43)	6.13	(2.94)
Water inlet pipe	2.85	(2.67)	4.39	(2.45)
Inlet diagram				
Handle	0.91	(0.91)	1.18	(0.72)
Siphon bell	4.39	(2.01)	11.54	(4.52)
Float + arrow 7	4.33	(1.84)	2.98	(2.38)
Inlet valve + arrow 5, 8	16.63	(8.33)	5.42	(3.00)
Water inlet pipe + arrow 6	9.02	(5.47)	5.63	(4.13)

Note. For the non-arrow group, all areas of interest on the outlet and inlet diagrams contained no arrows.

outlet-process diagram was higher in arrow group than the non-arrow group, $F(1, 38) = 4.36$, $p < .05$, $\eta^2 = .10$, but the two groups did not differ in proportion of fixation duration on the inlet-system diagram, $p > .10$. In addition, the proportion of fixation duration was higher for the outlet-process diagram than the inlet-process diagram for both groups, $F(1, 19) = 64.43$, $p < .001$, $\eta^2 = .77$; $F(1, 19) = 7.66$, $p < .05$, $\eta^2 = .29$.

For the *siphon bell* area of interest, there was no main effect of Arrow, $p > .10$, but there was a significant main effect of Diagram, $F(1, 38) = 103.65$, $p < .001$, $\eta^2 = .73$; the interaction between Arrow and Diagram was also significant, $F(1, 38) = 18.22$, $p < .001$, $\eta^2 = .32$. Simple main effects showed that the proportion of fixation duration on the outlet-process diagram was marginally greater for the arrow group than the non-arrow group, $F(1, 38) = 3.49$, $p = .069$, $\eta^2 = .08$, but the proportion of fixation duration on the inlet-process diagram, which had the same area as the outlet-process diagram, was higher for the non-arrow group than the arrow group, $F(1, 38) = 41.72$, $p < .001$, $\eta^2 = .52$. In addition, both groups had a higher proportion of fixation duration on the outlet-process diagram than on the inlet-process diagram, $F(1, 19) = 94.73$, $p < .001$, $\eta^2 = .83$; $F(1, 19) = 19.46$, $p < .001$, $\eta^2 = .51$.

For the *float* area of interest, there was a main effect of Arrow, $F(1, 38) = 8.04$, $p < .01$, $\eta^2 = .18$; the proportion of fixation duration on the areas of interest was higher in the arrow group than the non-arrow group. However, there was no main effect Diagram, nor was the interaction between Arrow and Diagram significant, $ps > .10$.

For the *inlet valve* area of interest, there were significant main effects of Arrow, $F(1, 38) = 18.85$, $p < .001$, $\eta^2 = .33$, and Diagram, $F(1, 38) = 28.62$, $p < .001$, $\eta^2 = .43$, and the interaction between Arrow and Diagram was also significant, $F(1, 38) = 35.57$, $p < .001$, $\eta^2 = .48$. Simple main effects showed that the proportion of fixation duration on the area of interest on the outlet-process diagram was marginally lower for the arrow group than the non-arrow group, $F(1, 38) = 9.58$, $p < .01$, $\eta^2 = .20$. Conversely, the proportion of fixation duration on the same area of interest in the inlet-process diagram was higher for the arrow group than the non-arrow group, $F(1, 38) = 32.08$, $p < .001$, $\eta^2 = .46$. In addition, for the arrow group, the proportion of fixation duration on the same area of interest area was higher for the inlet-process diagram than for the outlet-process diagram, $F(1, 19) = 37.69$, $p < .001$, $\eta^2 = .67$; the non-arrow group showed no significant differences between the two diagrams, $p > .10$.

For the *water inlet pipe* area of interest, there was no main effect of Arrow, $p > .10$, but there was a significant main effect of Diagram, $F(1, 38) = 16.77$, $p < .001$, $\eta^2 = .31$; the interaction between Arrow and Diagram was also significant, $F(1, 38) = 7.41$, $p < .05$, $\eta^2 = .16$. Simple main effects showed that the proportion of fixation duration on this area of interest in the outlet-process diagram was marginally lower for the arrow group than the non-arrow group, $F(1, 38) = 3.60$, $p = .065$, $\eta^2 = .09$. Conversely, the proportion of fixation duration on the same interest area of the inlet-process diagram was higher for the arrow group than the non-arrow group, $F(1, 38) = 4.89$, $p < .05$, $\eta^2 = .11$. In addition, for the arrow group, the proportion of fixation durations on the same area of interest was higher for the inlet-process diagram than the outlet-process diagram, $F(1, 19) = 16.23$, $p < .01$, $\eta^2 = .46$; the non-arrow group showed no significant differences between the two diagrams, $p > .10$.

3.2.4. Analyses of the sequence of eye fixations made on the diagrams

In order to examine the cognitive processes and reading strategies of both groups, we carried out a series of sequential analysis matrix calculations (Bakeman & Gottman, 1997) to analyze the sequence of eye fixations. We first calculated the fixation transition from each of ten areas of interest to others made on the two diagrams. The adjusted residuals are shown in Appendices A and B. The rows represent the starting interest areas and the columns represent the subsequent transfer areas. A Z-value greater than 1.96 indicated that the transfer sequence had reached the cutoff level of significance ($p < .05$). The results for both groups' first-pass and total pathways are reported below. As mentioned previously, the first-pass pathway reflects object encoding, and the total pathway reflects comprehension and integration.

3.2.4.1. First-pass fixation sequences for both groups. Fig. 4 gives first-pass transition diagrams for the arrow and non-arrow groups;

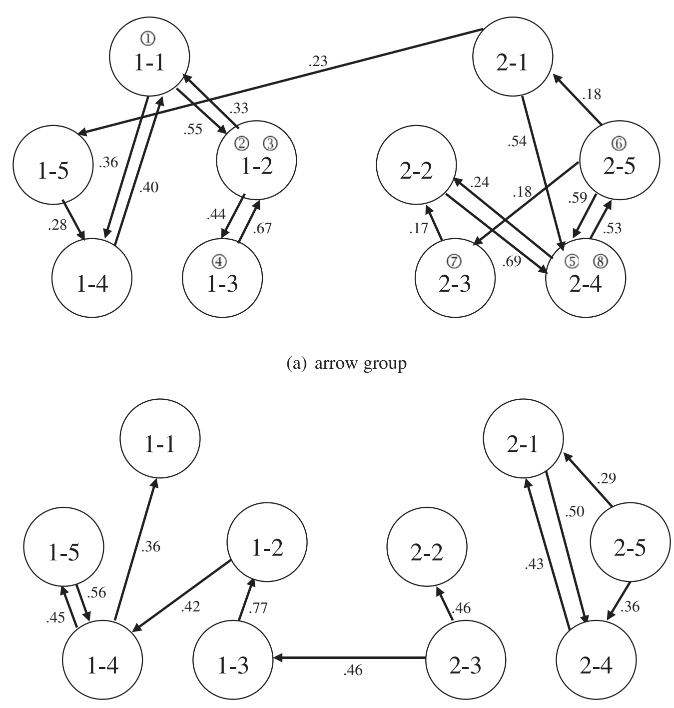

Fig. 4. First-pass transition diagrams for the arrow and non-arrow groups. The five circles on the left represent components on the outlet diagram, and the circles on the right represent components on the inlet diagram. The numbers beside the arrow indicators show the transition probabilities.

its Z-value matrix is shown in Appendix A. Overall, for first-path fixation, both groups tended to transfer their next fixations within the same diagram rather than crossing between the two diagrams. However, there were group differences in reading pathways.

Analysis of the first-pass pathway for the arrow group, Fig. 4(a) revealed two main findings.

The first was that the arrow group tended to locate their fixations on the components with numbered arrows and then either followed the sequential numbers or fixated back to the previous components after first leaving the target area. On the outlet diagram, the transfer probability of *handle and arrow 1* to *siphon bell and arrow 2 and arrow 3* was significantly higher than that of other interest areas, $Z = 2.84$, $p < .05$, and the same was true for the reverse order of transfer, $Z = 2.72$, $p < .05$. The transfer probability of *siphon bell and arrow 2 and arrow 3* on the outlet diagram to *float and arrow 4* on the outlet diagram were significantly higher than that of other interest areas, $Z = 6.11$, $p < .05$; the same was true for the reverse transfer, $Z = 4.55$, $p < .05$. On the inlet diagram, the transfer probability of *inlet valve and arrow 5 and arrow 8* to *water inlet pipe and arrow 6* was significantly higher than that of other interest areas, $Z = 5.25$, $p < .05$; the same was true for the reverse transfer, $Z = 3.55$, $p < .05$; the transfer probability of *water inlet pipe and arrow 6* to *float and arrow 7* was significantly higher than that of other interest areas, $Z = 2.17$, $p < .05$.

The second finding was that, after the first scan, the arrow group tended to locate their fixations on the components spatially nearby the previous target components (or their connected components). The *handle* and *inlet valve* were close to each other on both diagrams and results showed that the arrow group had higher transfer probabilities of *handle and arrow 1* to *inlet valve* on the outlet diagram, $Z = 2.93$, $p < .05$, and for the reverse transfer, $Z = 3.33$, $p < .05$. The arrow group also had higher transfer probabilities of *handle* to *inlet valve and arrow 5 and arrow 8* on the inlet diagrams, $Z = 2.72$, $p < .05$. In addition, the *inlet valve* and *water inlet pipe* were spatially near to each other and appeared to be connected on the diagrams; the arrow group had higher transfer probabilities of *water inlet pipe* to *inlet valve* on the outlet diagrams, $Z = 2.44$, $p < .05$, and on the inlet diagram, $Z = 3.55$, $p < .05$. When transfer probabilities were tested in reverse order, results for the inlet diagram were also significant, $Z = 5.25$, $p < .05$.

For the first-pass pathway, the non-arrow group did not look back and forth between specific areas as frequently as did the arrow group (Fig. 4(b)). Presumably, this was because the non-arrow group did not see any numbered arrows on the diagrams. However, participants in the non-arrow group still tended to locate their next fixations on the components that were spatially nearby the previously viewed components (or their connected components). The non-arrow group had higher transfer probabilities of *inlet valve* to *handle* on the outlet diagram, $Z = 4.55$, $p < .05$, and on the inlet diagram, $Z = 3.71$, $p < .05$. When transfer probabilities were tested in reverse order, results for the inlet diagram were also significant, $Z = 3.87$, $p < .05$. In addition, the non-arrow group had higher transfer probabilities of *inlet valve* to *water inlet pipe* on the outlet diagrams, $Z = 3.89$, $p < .05$; the same was true for the reverse order of transfer, $Z = 4.22$, $p < .05$. They also had higher transfer probabilities of *inlet valve* to *water inlet pipe* on the inlet diagram, $Z = 2.34$, $p < .05$.

3.2.4.2. Total-pass fixation sequences for both groups. Fig. 5 gives total-pass transition diagrams for arrow and non-arrow groups; its Z-value matrix is shown in Appendix B. Overall, the patterns of the total-pass transition diagrams for both groups were more dispersive than that of the first-pass. This pattern might indicate that many components are involved in the construction of kinematic representations, that is, learners must speculate about the inner operations among several components to infer cause-and-effect relations at a later processing stage. However, there were some distinct group differences.

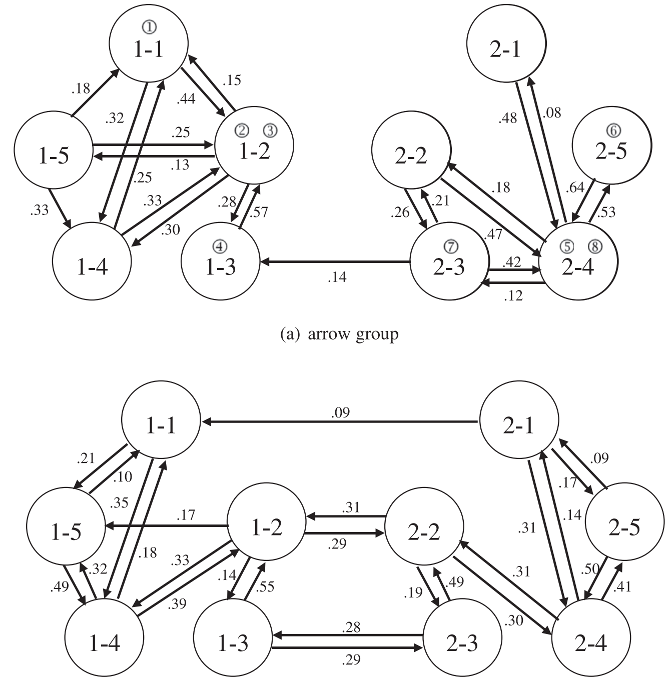

Fig. 5. Total-pass transition diagrams for the arrow and non-arrow groups. The five circles on the left represent components on the outlet diagram, and circles on the right represent components on the inlet diagram. The numbers beside the arrow indicators give the transition probabilities.

The analysis of total-pass pathway for the arrow group (Fig. 5(a)) showed that components with numbered arrows remained a focus. On the outlet diagram, the transfer probability of *handle and arrow 1* to *siphon bell and arrow 2 and arrow 3* was significantly higher, $Z = 9.06$, $p < .05$, and a similar result was found for the reverse transfer, $Z = 5.06$, $p < .05$. The transfer probability of *siphon bell and arrow 2 and arrow 3* on the outlet diagram to *float and arrow 4* on the outlet diagram was significantly higher than for other interest areas, $Z = 15.01$, $p < .05$, and for the reverse transfer, $Z = 15.04$, $p < .05$. On the inlet diagram, the transfer probability of *inlet valve and arrow 5 and arrow 8* to *water inlet pipe and arrow 6* was significantly higher than for other interest areas, $Z = 18.47$, $p < .05$, and for the reverse transfer, $Z = 18.18$, $p < .05$. The transfer probability of *float and arrow 7* to *inlet valve and arrow 5 and arrow 8* was significantly higher than for other interest areas, $Z = 6.88$, $p < .05$, and was higher for the reverse transfer, $Z = 2.71$, $p < .05$.

Additionally, spatial continuity remained a focus in the total-pass pathway. The arrow group had higher transfer probabilities of *handle and arrow 1* to *inlet valve* on the outlet diagram, $Z = 7.45$, $p < .05$, and higher probabilities on the reverse transfer, $Z = 10.14$, $p < .05$. On the inlet diagram, the sequential patterns of *handle* and *inlet valve* (in both directions) were significantly different from patterns in other interest areas, $Z = 5.68$, $p < .05$, $Z = 4.89$, $p < .05$. In addition, the arrow group had higher transfer probabilities of *water inlet pipe* to *inlet valve* on the outlet diagrams, $Z = 8.55$, $p < .05$, and on the inlet diagram, $Z = 18.18$, $p < .05$. When the reverse order of transfer was tested, the transfer probability remained significant, $Z = 18.47$, $p < .05$.

The analysis of total pathway for the non-arrow group (Fig. 5(a)) showed that the non-arrow group tended to compare the same components between the two diagrams. For example, they had a significantly higher transfer probability of *handle* on the inlet diagram to *handle* on the outlet diagram, $Z = 4.08$, $p < .05$; they also had significantly higher transfer probability of *siphon bell* from the outlet to inlet diagrams, and when probability was tested in reverse order, $Z = 3.39$, $p < .05$; $Z = 1.99$, $p < .05$. A similar result was found for *float* between the two diagrams ($Z = 11.18$, $p < .05$; $Z = 11.27$, $p < .05$).

We also found that, after leaving the target components, the non-arrow group tended to locate their fixations on the components that were spatially nearby the previous target components (or their connected components). This group had higher transfer probabilities of *handle* to *inlet valve* on the outlet diagram, $Z = 5.12$, $p < .05$ and for reverse order of transfer, $Z = 6.64$, $p < .05$. A similar result was found for the inlet diagrams (handle to inlet valve, $Z = 6.13$, $p < .05$; reverse probability, $Z = 6.68$, $p < .05$). For the *water inlet pipe* to *inlet valve* components there was a significant difference in transfer probability on the outlet diagram when compared to other components, $Z = 5.81$, $p < .05$, for the reverse order, $Z = 10.66$, $p < .05$, and for transfer probability on the inlet diagrams ($Z = 2.62$, $p < .05$; $Z = 8.47$, $p < .05$).

4. Discussion and conclusion

The present study investigated how learners construct kinematic representations of a mechanical system by reading static diagrams either with or without numbered arrows. We were interested not only in examining the construction process, but also in the learning outcomes of the kinematic mental model.

An important advantage of our study is that it adapted the statistical method of sequential analysis, which is typically used to describe interaction process relations to analyze eye-movement data. Unlike previous research (Kriz & Hegarty, 2007), where inferences about cognition were made from measurements on one dimension (percentage of fixations on areas of interest), in the present study we conducted a detailed analysis using several eye-movement indicators. We also examined sequences of eye fixations by conducting sequential analyses of transition probabilities from all areas of interest in relation to one another. Although other factors (e.g., coulometer, low-level physical features of the stimulus, etc.) may not be excluded to influence eye movement measures, the assumption of an eye-mind link is an important basis for the use of eye-tracking in cognitive research. Compared with single eye-movement indicators as used by Kriz and Hegarty (2007), we used multiple eye-movement indicators and sequential analysis of eye fixations may provide convergent evidence to infer the cognitive processes involved in the reader's construction of a mechanical kinematic representation.

Our first research question asked whether numbered arrows on diagrams would provide not only conceptual guidance but also facilitation of cognitive processing. Indeed our results confirmed that the two groups experienced different forms of cognitive processing. The arrow group followed the numbered arrows whereas the unique pathway of the non-arrow group was to compare the two diagrams.

As predicted by Hypothesis 1a, the step-by-step question indicated that the arrow group constructed a better kinematic mental model than did the non-arrow group. The arrow group appeared to be more accurate (42%) than the non-arrow group (18%) thus indicating that they had formed a partial, and likely better, mechanical kinematic representation. This finding is consistent with previous research arguing that arrows on diagrams can convey dynamic information (Heiser & Tversky, 2006; Kriz & Hegarty, 2007; Mayer & Gallini, 1990).

Consistent with Hypothesis 1b, the eye-movement data showed that arrow and non-arrow groups experienced different cognitive processing. There are several lines of evidence suggesting that the arrow group tended to follow the numbered arrows on the diagram back and forth at the initial processing stage (to construct their local kinematic representation) and then combined several local representations, inferring the cause-and-effect chain of processes at the late processing stage. First, the arrow group had a greater proportion of fixation duration on the components with numbered arrows than those having no numbered arrows (on both diagrams). Second, the arrow group had longer first-pass fixation time on both diagrams than did the non-arrow group. It is worth noting that the arrow group had a first-pass fixation time twice as large as that of the non-arrow group. These data suggest that the arrow group used more cognitive resources when: (1) reading the outlet-process diagram (first diagram), (2) trying to construct the kinematic representation, and (3) inferring the cause of each sequential and connected component. Third, the sequential transition probabilities provided direct evidence for the process of kinematic representation formation. After the first pass, the arrow group had significantly higher transition probabilities on the components that had continuous numbered arrows. In addition, their transition probabilities became dispersive at the late processing stage (total pathway) indicating that there were many components involved in the process of constructing a kinematic representation when arrows were provided.

The step-by-step question showed that the arrow group outperformed the non-arrow group and we therefore inferred that numbered arrows facilitate cognitive processing. However, this is not to say that adult readers cannot learn kinematic information from reading diagrams. For example, when the two diagrams were analyzed separately, the group discrepancy in mean saccade length vanished. This suggests that the distribution of fixations on the individual diagrams was similar for the two groups; that is, both groups looked at the majority of important components of the flushing cistern on the two diagrams. If the arrow group had looked only at areas near the arrows and not at the components indicated by the arrows, mean saccade length on the diagrams would have been shorter; this was not observed. Thus, our analyses indicate that numbered arrows on static diagrams serve not only a perceptual function, but also facilitate cognitive processing and construction of a better kinematic representation.

Our second research question concerned which properties of kinematic representation were affected by numbered arrows on the diagrams and what cognitive processes occurred.

As predicted by Hypothesis 2a, the arrow group outperformed the non-arrow group on the continuous relation measure. Although the arrow group had higher accuracy on the step-by-step question than did the non-arrow group, this improvement was only evident on the continuous relations questions. It is inappropriate to evaluate whether a reader's mental model is correct or incorrect; rather, it is more meaningful to evaluate how close a reader's mental model is to being complete (Hegarty et al., 2003; Kriz & Hegarty, 2007). Thus, in addition to investigating the degree of completeness of readers' kinematic representations, we were also concerned with errors in the formed representations. By analyzing three error types, we found that the arrow group made fewer continuous relation errors than did the non-arrow group, but the two groups did not differ on the other two error types (direction alteration and order relation). All participants made few errors of these types. This suggests that mastering the continuous (and changing) relationships between components may be crucial to forming a better mechanical kinematic representation. Order-relation and direction-alteration properties may be less important than the continuous relationships.

Why did diagrams with numbered arrows produce different effects on the three properties of mechanical kinematic representations? One possible explanation is that there was a ceiling effect on the errors of order relation and direction-alternation relation. Learning global or temporal relationships (corresponding to order relation errors) and global spatial relationships (corresponding to direction alteration errors) is generally easy for adult readers. Consequently, readers seldom make errors for distant casual events or locations. Flushing cistern components were contained in a mechanical structure that does not exist in isolation and adult readers usually have some basic schema for mechanical systems. For example, even with minimal background knowledge, most people recognize that a handle is unlikely to be located underneath a flushing cistern. Therefore, it is possible that the numbered arrows had no effect on mastery of order and directional relationships. However, forming an intact kinematic representation requires remembering a lot of detailed information, including components' configurations and their local serial relations (corresponding to continuous relation errors). This is not an easy task because human working memory capacity is limited (Baddeley, 2000; Paas, Renkl, & Sweller, 2003). Thus, it is reasonable to conclude that the numbered arrows had an effect only on the continuous relation property of kinematic representations.

In the present study, Hypothesis 2b was not completely supported. Although we expected the groups to deal with continuous relations of components in different ways, our data showed that both groups had significantly higher transfer probabilities on components located close to each other on the diagrams. The arrow group remained focused on the relations of components nearby or connected to one other in a manner similar to the non-arrow group. An interesting question is, what was the strategy used by the non-arrow group? Without visual cues on the diagrams, how did the non-arrow group infer the processes of the flushing cistern sufficiently to succeed on the experiment tasks? We found that these participants tried to construct a local representation of continuous relations between components at the initial processing stage; the first-pass transition indicated that the non-arrow group had significantly higher transition probabilities on the components that were close to each other. They appeared to compare the differing status of the diagrams to infer the possible processes at the late processing stage; the total-pass transition diagram indicates they had significantly higher transition probabilities on the same components of both diagrams. This is consistent with previous research indicating that comparing the different status of diagrams is a common strategy for understanding a concept conveyed in diagrams, especially for low-knowledge readers (Cook, Carter, & Wiebe, 2008).

In the present study, we found that numbered arrows on static diagrams were more effective than they were in the previous Hegarty et al. (2003) study. This was unexpected because according to conventional wisdom, an animation should be helpful for readers to form a better kinematic representation because an animation is composed of many static diagrams and provided more information than a single static diagram. However, this conjecture is not supported by the current findings.

The limits of working memory capacity (Baddeley, 2000; Paas et al., 2003) are often used to explain why static diagrams are more helpful for readers than is animation (Höffler & Leutner, 2007). The animation used by Hegarty et al. (2003) and the two-stage static diagrams in the present study both utilized eight arrows to indicate the same components and locations on the flushing cistern. However, the arrows displayed on the animation are shown one at a time, and change as the flushing cistern operates. Under these conditions, readers need to process new information while the arrows are shown briefly. For example, in addition to remembering what the start and end components are, readers need to remember the direction and location of the information indicated by each arrow. In addition, readers need to remember where and what the previous arrow indicated, and then integrate the old and new information to form a kinematic representation. Due to cognitive load, it is unlikely that participants could process this amount of complex information simultaneously (Paas et al., 2003). Therefore, it is not surprising that an effect of arrows on animation has not been observed. Indeed, arrows on an animation might act mainly at the perceptual level, attracting readers' attention, as shown by Hegarty et al. (2003).

Importantly, in the present study, eight arrows labeled serial numbers on the diagrams, and thus readers did not need to keep all of the diagram information in working memory. Therefore, there was likely sufficient working memory capacity to carry out high-level cognitive processing such as inferring how a flushing cistern works by using the information in the diagrams. If the information decayed from working memory before being processed further, readers were able to re-read the arrows at any time, repeatedly, until they formed a good mental representation. This phenomenon was observed in the present study and may explain why, when learning the same scientific concept (i.e., how a flushing cistern works), the undergraduates in our study (who read static two-stage diagram with numbered arrows) remembered more correct steps than did the undergraduates who saw an animation with arrows (Hegarty et al., 2003).

Although the present study makes several useful contributions, some limitations need to be considered. First, the participants were adults and were low-knowledge readers of mechanical diagrams. Therefore, the current results may not generalize to populations of children or high-knowledge readers. Second, the learning material included only two diagrams about a mechanical system. Future studies should investigate the processes of kinematic representation using a more complicated degree of kinematics.

In sum, the present study provides direct evidence to describe different reading pathways during the formation of a kinematic representation. The arrow group apparently adopted the strategy of following the numbered arrows to construct a kinematic representation of how the flushing cistern worked. However, the non-arrow group adopted a different strategy by comparing the differing status of the same components between outlet and inlet diagrams. Common reading characteristics shared between the two groups were that they tended to fixate on those components nearby or connected to each other. Our findings indicate that continuous relations are important cues for learners who are constructing kinematic representations while reading static diagrams.

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Appendix A

Z-value matrix of the first-pass sequences for arrow and non-arrow groups.

Target area	1-1#	1-2#	1-3#	1-4	1-5	2-1	2-2	2-3#	2-4#	2-5#
Start area										
Arrow group										
1-1#		2.84*	0.21	2.93*	−0.77	−0.77	−0.85	−0.84	−1.85	−1.32
1-2#	2.72*		6.11*	0.84	0.11	−1.04	−1.14	−1.13	−2.48	−1.77
1-3#	0.08	4.55*		0.36	0.33	−0.96	−1.05	−1.04	−2.29	−1.63
1-4	3.33*	1.83	−1.17		1.58	0.32	−1.02	−1.01	−2.21	−1.58
1-5	1.24	1.24	−1.31	2.44*		−1.04	−1.14	−0.07	−2.48	−0.32
2-1	−1.41	−1.92	−1.07	−1.28	3.19*		0.30	−0.93	2.72	0.25
2-2	−1.45	−1.26	−1.11	−1.32	−0.87	−0.88		1.60	4.18*	−0.62
2-3#	−1.72	−1.74	−0.38	−1.56	−1.03	1.24	2.01*		1.56	1.13
2-4#	−1.77	−2.41	−1.35	−0.74	−1.07	0.16	3.38*	1.13		5.25*
2-5#	−1.66	−2.26	−0.31	−1.51	−1.00	2.51*	−1.10	2.17*	3.55*	
Non-arrow group										
1-1		0.46	0.20	1.08	−0.06	−0.17	−1.14	−0.82	−1.34	1.37
1-2	0.40		1.09	2.31*	1.70	−1.36	−1.30	0.37	−1.54	−1.14
1-3	−0.94	6.43*		−1.75	−0.38	−1.39	−1.33	1.49	−1.56	−1.16
1-4	4.55*	−0.57	0.09		3.89*	−1.26	−1.20	−0.86	−1.42	−1.05
1-5	0.05	−1.88	−1.35	4.22*		−0.81	0.15	−1.12	−1.08	0.55
2-1	0.21	−1.67	−1.21	−0.38	−0.47		0.40	0.18	3.87*	−1.21
2-2	−1.04	1.72	−1.27	−1.93	−1.45	0.40		0.27	1.81	0.97
2-3	−0.97	−1.65	5.21*	−1.80	−1.35	−1.43	4.33*		−1.61	−0.13
2-4	−0.98	−0.90	−1.21	−1.10	−0.47	3.71*	0.40	−1.00		1.78
2-5	−1.01	−1.73	−1.25	−1.14	−0.49	2.03*	−0.52	1.39	2.34*	

Note. "#" represents numbered arrow(s) on this area. The number "1" indicates the outlet diagram: 1-1 was *handle* (# arrow 1), 1-2 was *siphon bell* (# arrow 2 and 3), 1-3 was *float* (# arrow 4), 1-4 was *inlet valve*, 1-5 was *water inlet pipe*. The number "2" indicates the inlet diagram: 2-1 was *handle*, 2-2 was *siphon bell*, 2-3 was *float* (# arrow 7), 2-4 was *inlet valve* (# arrow 5 and 8), 2-5 was *water inlet pipe* (# arrow 6). For the non-arrow group, there were no arrows on either the inlet or the outlet diagrams.
*$p < .05$.

Appendix B

Z-value matrix of the total-pass sequences for arrow and non-arrow groups.

Target area	1-1#	1-2#	1-3#	1-4	1-5	2-1	2-2	2-3#	2-4#	2-5#
Start area										
Arrow group										
1-1#		9.06*	−1.13	7.45*	0.94	−0.50	−2.88	−3.15	−5.18	−4.06
1-2#	5.06*		15.01*	10.32*	3.74*	−3.45	−3.01	−4.32	−8.95	−8.43
1-3#	−0.83	15.04*		−0.74	−0.45	−2.46	−2.17	1.03	−5.05	−5.55
1-4	10.14*	7.44*	−2.25		10.82	−1.53	−4.95	−4.36	−5.61	−6.36
1-5	5.17*	3.35*	−2.43	8.55*		−1.90	−3.74	−3.27	−4.38	−1.56
2-1	−0.86	−3.45	−2.22	−0.93	0.14		−1.31	−0.89	5.68*	1.54
2-2	−3.17	−2.51	−3.38	−3.87	−3.48	−1.84		8.80*	7.77*	−0.49
2-3#	−4.03	−3.89	3.75*	−4.85	−4.00	−1.40	5.56*		6.88*	−0.86
2-4#	−7.31	−8.81	−6.64	−7.65	−5.94	4.89*	5.14*	2.71*		18.47*
2-5#	−5.31	−6.79	−4.62	−5.68	−3.18	1.94	0.32	0.78	18.18*	
Non-arrow group										
1-1		−0.14	−0.09	5.12*	3.40*	1.47	−3.46	−2.74	−2.12	−1.11
1-2	0.44		5.98*	7.23*	3.37*	−3.05	3.39*	−4.29	−5.02	−5.24
1-3	−4.28	13.39*		−5.51	−3.25	−4.96	−10.91	11.18*	−9.31	−7.15
1-4	6.64*	3.31*	−1.27		5.81*	−0.74	−3.27	−2.36	−1.70	−1.66
1-5	4.59*	−2.04	−0.63	10.66*		−0.97	−4.40	−3.46	−2.78	1.14
2-1	4.08*	−5.55	−2.59	−2.36	−0.06		1.44	−3.08	6.13*	2.48*
2-2	−1.41	1.99*	−1.77	−3.00	−2.53	−0.02		2.62*	4.21*	1.31
2-3	−1.79	−3.06	11.27*	−3.81	−3.22	−2.08	8.47*		−2.54	−0.67
2-4	−2.16	−6.18	−2.91	−5.36	−2.26	6.88*	4.48*	−3.76		13.87*
2-5	−2.81	−6.58	−3.53	−5.24	−0.82	3.41*	1.40	−3.70	15.40*	

Note. "#" represents numbered arrow(s) on this area. The number "1" indicates the outlet diagram: 1-1 was *handle* (# arrow 1), 1-2 was *siphon bell* (# arrow 2 and 3), 1-3 was *float* (# arrow 4), 1-4 was *inlet valve*, 1-5 was *water inlet pipe*. The number "2 indicates the inlet diagram: 2-1 was *handle*, 2-2 was *siphon bell*, 2-3 was *float* (# arrow 7), 2-4 was *inlet valve* (# arrow 5 and 8), 2-5 was *water inlet pipe* (# arrow 6). For the non-arrow group there were no arrows on either the inlet or the outlet diagrams.
*$p < .05$.

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