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Instructional Suggestions Supporting Science Learning in Digital Environments Based on a Review of Eye Tracking Studies

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ABSTRACT

The main purpose of this study was to provide instructional suggestions for supporting science learning in digital environments based on a review of eye tracking studies in e-learning related areas. Thirty-three eye-tracking studies from 2005 to 2014 were selected from the Social Science Citation Index (SSCI) database for review. Through a literature analysis program, CATA, and in-depth content analysis of the research methods and findings, five research theme clusters were abstracted from the selected papers, namely, cognitive activities in processing multimedia presentations, multimedia effects, roles of personal factors, effects of instructional design, and learning with dynamic e-platforms. Based on the results of the in-depth theme analyses, it is suggested that the design of e-learning instruction should consider placing related text and graphics in adjacent areas, using one verbal mode at a time, and providing explicit and clear verbal explanations. When using animations, instructors need to explain carefully the goals and contents of the animations to reduce the extraneous cognitive load. In the dynamic learning environment, a pre-training program is necessary for students to become familiar with the new environment. Finally, individual differences such as background knowledge, cognitive abilities and cognitive styles should be taken into consideration in the instructional design.

Keywords

Instructional design, Eye tracking, Digital learning, Digital learning environment, Science learning

Introduction

With the rapid development of digital technologies such as the Internet, multimedia and mobile devices, the conventional learning environments with the blackboard as the main presentation platform have gradually evolved into electronic classrooms. The infusion of technologies into teaching and learning has given rise to new paradigms of learning, including multimedia learning, web-based inquiry learning, computer supported collaborative learning, game-based learning, e-learning, mobile learning and so forth (e.g., Mayer, 2014; Slotta, Linn, & Lee, 2009; Lai, Hwang, Liang, & Tsai, 2016). It is believed that technologies function as tools to support knowledge construction, as information vehicles for exploring knowledge, as media to support learning-by-doing, as social media to support cooperative learning and communication, and as intellectual partners to support learning-by-reflecting (Jonassen, Peck, & Wilson, 1999; Goodyear & Retalis, 2010; Hwang & Wang, 2016;). Practically, the use of technologies is more prevalent in science classrooms due to the close link between the process of knowledge construction in science and the use of technologies. In the science education literature, significant numbers of studies regarding digital learning have been accumulated (e.g., Lee, Tsai, & Wu, 2011; Tang & Tsai, 2016).

Although numerous studies related to the use of technologies in classrooms have been reported, there are scholars who have questioned the effectiveness of the use of technologies in assisting teaching and learning (e.g., West, Wright, Gabbitas, & Graham, 2006; Cheung & Slavin, 2013; Noesgaard & Orngreen, 2015). Indeed, because of their rapid development, new technologies are often applied to classrooms without in-depth examination of their impacts on learning before implementation. To address this issue, researchers who study the use of digital technologies in classrooms are paying attention to not only whether these technologies can improve students' learning performance, but also to how they can assist student learning (e.g., Chang & Yang, 2010; Groff, Howells, & Cranmer, 2012). To explore the latter issues, methods that can reveal how students learn with technologies are preferred. Surveys and content analysis of video data, computer log files, or interview data are frequently employed for that purpose (e.g., Groff, Howells, & Cranmer, 2012; Ryoo & Linn, 2014; Shirley &

Irving, 2015). Although the above-mentioned data types are records of learning behaviors, they are limited in terms of revealing the real-time actions and changes of mind during learning.

A promising method capable of recording online cognitive activities is the eye tracking method. Based on the eye-mind hypothesis (Just & Carpenter, 1980) that what is fixated on is processed, the eye tracking method has been developed to study mechanisms of information processing and a variety of cognitive processes (e.g., Rayner, 2009; Gidlöf, Wallin, Dewhurst, & Holmqvist, 2013). In addition to cognitive activities, the method is also applied to research areas such as human-computer interaction and usability research (Jocab & Karn, 2003; McEwen & Dubé, 2015). In eye tracking studies, researchers use eye tracking measures to indicate learners' or users' visual attention, workload or mental effort expended during a task. Fixations and saccades are the two major eye movements identified by eye trackers. The former refers to a relatively stable state of eye movement, while the latter refers to the rapid movement between any two consecutive fixations (Rayner, 2009). Eye tracking measures, which are generally categorized according to temporal, spatial and frequency scales (Lai et al., 2013), are usually analyzed and reported based on areas of interest (AOIs) as defined in individual studies. Depending on the research questions, eye tracking measures are selected or analyzed differently with respect to different study purposes (Holmqvist et al., 2011).

The use of eye tracking methods in educational studies has proliferated only in recent years. According to Lai et al. (2013), before 2009, few educational studies had used such methods, probably due to the lack of communication between the fields of education and psychology, and the high cost of the equipment. The review study by Lai and colleagues found that two major issues discussed by the educational researchers who applied eye tracking methods in their studies are patterns of information processing and effects of instructional designs. It is interesting to note that in the work of Lai et al. (2013), quite a few papers concerning the instructional designs are related to multimedia learning. Nevertheless, how the eye tracking method can reveal the use of technologies in assisting science learning has not been systematically analyzed. Given that the employment of multimedia or digital technologies in the science classroom is an unavoidable trend, we have thus made an attempt to review eye-tracking studies regarding science learning in multimedia as well as technology-enhanced environments (we call such environments, "digital learning environments"). Drawn from the review, we hope to propose suggestions for future instructional design supporting learning in digital learning environments.

Method

The empirical papers included in the study came from the Social Science Citation Index (SSCI) database. To select suitable papers, the keywords of "eye tracking" and "eye movement" were combined with "multimedia learning," "e-learning," "digital learning," "learning technology," "educational technology," "mobile learning," and "ubiquitous learning," using the Boolean operator "AND." The years spanned from 2005 to 2014. There were 91 papers extracted from the first round of the search process. The same keyword combinations were then put together using the Boolean operator "OR." Consequently, 46 of the original 91 papers remained. Afterwards, the researchers manually inspected the studies. Those involving non-science subject areas, non-human subjects, subjects with medical impairment or special needs, or which were conducted in out-of-school contexts were excluded from the analysis. In addition, only empirical studies were retained. As a result, a total of 33 papers, including 36 studies, were selected from the SSCI database for this review.

To categorize the characteristics of the selected papers, we used a paper analysis program, Content Analysis Toolkit for Academic Research (CATA), to do the initial grouping. The program, using data mining technology, was developed by Yseng and Tsay (2013), and is able to analyze the similarity of papers in accordance with the keywords, citations, authors and so forth. The quality of CATA has been compared to other similar data miming systems (such as infoMap developed by Computational Semantics Library at Stanford University), and the result suggested that the method is highly reliable (for more details, see Tseng, 2010). Since CATA classifies academic papers in accordance with similarities among papers, problems of subjectivity and uncertainty caused by content analysis alone can be reduced. In other words, instead of researchers alone determining the structure of these selected papers, CATA allows the papers themselves to reveal their structure. The preliminary analysis by CATA suggested that the 33 papers analyzed in the study fell into 7 clusters with 4 unidentified.

After the CATA analysis, the researchers reviewed and examined the paper contents to determine the relevance of the papers in each cluster, and reassigned papers to different clusters if necessary. Among the seven clusters abstracted by CATA, two consisted of only two papers. After examining their contents, they were re-assigned to different clusters. In short, as a triangulation process, CATA and content analysis complemented each other to help the researchers identify possible research themes embedded in the selected papers. As a result, five research themes as will be introduced later were determined.

After all the selected papers were assigned to their proper categories, they were analyzed in-depth according to their research purposes, subjects, models of eye trackers, learning topics, eye movement measures and indications, instructional materials, experimental design, performance measurements and research results. It should be noted that the learning topics and types of eye movement measures were analyzed based on the categories of learning topics and eye movement measures mentioned in the study of Lai et al. (2013) The review task went through intensive discussions by all the authors of the paper; therefore, there was no issue of inter-coder reliability.

Result and discussion

General characteristics of the reviewed papers

Among the 36 studies (from 33 papers), the majority (n = 26) recruited research subjects at universities or colleges. In only seven papers were the research subjects K-12 students. The remaining three papers studied adult learners, including university students, medical professionals, and surgical residents. In terms of learning topics, conceptual development received the most attention (27 studies). There are 5 studies focusing on skill or strategy learning, and the rest 2 studies on perception.

In contrast to the reading studies that frequently employ eye-tracking systems with high sampling rates (> 500Hz), eye trackers with sampling rates of 50Hz ad 60Hz were the most popular types of systems mentioned in the reviewed papers. In the searched studies, eye movements were measured using the following indicators: fixation frequency and duration, gaze frequency and duration, saccade frequency and duration, scan path, reading time, and transitions between different representations. We further categorized the eye movement indicators into temporal, spatial, and count measures. Almost all the papers collected temporal measures of eye movement (34 studies), followed by spatial measures (18 studies) and frequency measures (15 studies). Evidently, temporal eye movement measures were used in almost all studies to indicate the time needed to process information, and those that revealed the attention allocations and spatial sequences, such as the number of fixations on different AOIs, regression counts, and scan paths, were frequently reported.

The above-mentioned eye movement measures reflect learners' online cognitive activities that should explain consequent learning behaviors or performances. In most of the reviewed papers, the behavior or performance measurements included, in general, three major types, namely, achievement test, skill/ability test, and performance exam. Achievement tests included prior knowledge tests, comprehension tests, delayed/retention tests, and transfer tests. Several studies utilized tests to examine students' skills or abilities such as visualization tests, spatial ability tests, and visual memory tests. Performance exams, such as knot tying performance and diagnostic performance, were conducted in the studies on medical knowledge. Other qualitative data were collected through think-aloud when completing the tasks, verbal responses to questions, and interviews.

Research themes abstracted from the study findings

As mentioned, the researchers of this study cross-examined the result of CATA analysis. Subsequently, five clusters of research theme were abstracted, illustrated as follows.

Cluster 1 – Cognitive activities for processing multimedia presentations

Cluster one discusses the information processing activities for different forms and combinations of representations. There are ten papers in this cluster. The learning topics of these papers focus on conceptual development, with one exception that dealt with strategy learning (#19). Participating subjects included university students (6 studies), high school students (two studies) and elementary learners (one study). Four studies used text-based material with text-picture presentations as the learning material (#9, #13, #16, # 28, & #33), three involved visual representations such as image, animation or simulation (#2, #19 & #20), and the remaining three (#18, #21, & #33) examined the reading of WebPages. The multimedia representations included text, graphics, animation, simulation, and narration. Eye trackers with sampling rates of 60Hz were the most popular system. As for the eye movement measures, fixation related measures were reported most frequently, showing the processing time and attention locations as well as distributions. One study (#19) found that the fixation duration corresponded to the use of problem-solving strategies. Scan paths (i.e., saccades or transitions between different interest areas) were used to indicate the information integration strategies. Three studies (#16, #18, & #33) employed the measure of pupil dilation, while another used the fixation duration and saccade length to indicate cognitive load.

Several important findings can be summarized from the studies in this cluster. It was found that when written text and pictures were presented together, readers attended more to the written text than to the graphics. Nevertheless, when the graphics were in a conceptual, sequential or interactive form, the visual attention and processing time of the target areas increased. It was found that spoken text and background knowledge played a role in guiding visual attention. While spoken text seemed to increase visual attention to and processing time of the interest areas, background knowledge was found to reduce the processing time. When spoken text and written texts with the same content appeared together, the cognitive load increased. Meanwhile, animations, while attracting readers' attention, might result in extraneous cognitive load. For concept learning, these studies consented that the reading of texts or graphics alone could not predict the concept achievements. Instead, it was the information integration strategies, such as scanning or transitions between different representations, which were related most to the concept achievements. Additionally, an initial glance at the picture seemed to provide a mental scaffold for text reading. In short, the studies in this cluster suggest that learning from multimedia presentations requires learners to strategically distribute their attention to the interest areas and integrate information from different types of representation.

Cluster 2 – Multimedia effects

The theme of Cluster 2 is centered on examining multimedia effects as suggested by the cognitive load theory (Chandler & Sweller, 1992) and the theory of multimedia learning (Moreno & Mayer, 1999). There are five papers (#7, #8, #15, #24, and #26) in this cluster, in which eight studies were involved. The various multimedia effects include the visualization (multimedia representation) effect, the seductive details effect (coherence effect) (#7), the spatial contiguity effect (#15, #26), and the text-modality (split-attention) effect (#8, #24, #26). Specifically, the seductive details effect discusses how interesting but unimportant text and illustrations affect learning performance. The visualization effect discusses how decorative and instructional pictures paired with text affect learners' distribution of attention. The spatial contiguity effect discusses how integrated presentation (printed words close to corresponding graphics) and separate presentation (printed words at the bottom of the screen) affect learners' cognitive processing. The text modality effect discusses whether written text and spoken text affect learners' viewing behaviors and learning outcomes. Among the eight studies, except for one study that involved 7th and 8th graders (#8), all participants were university or graduate students. The eye-trackers employed by these studies had sampling rates ranging from 50Hz to 250Hz. Regarding the eye movement measures involved, all of these eight studies analyzed the spatial measures (e.g., number of switches (regressions) or transitions between text and visualizations) as well as the frequently observed temporal measures (e.g., gaze duration and viewing time), indicating that a great deal of attention was paid to how multimedia presentations may interact with information integration behaviors.

Analysis on the findings of these papers showed that seductive text passages and illustrations were found to hinder the transfer performance differently, but not the retention performance (#7). Pictures that are decorative by nature were found to be neither harmful to nor beneficial for learning. However, it was found that decorative pictures moderated the beneficial effect of instructional pictures for learners with low prior knowledge (#8). Learners' eye movement patterns suggested that an integrated presentation led to more integrative transitions and corresponding transitions compared to the separate presentation (#15). Visualizations were processed more when coupled with spoken text than with written text (#24, #26). Moreover, when animations were presented, learning performance was related to the reading time spent on the animations (#26).

Cluster 3 – Roles of learner factors

The theme of Cluster 3 constructed from the reviewed studies was centered on comparing the learning behaviors or performances of participants with different backgrounds or preferences. Six studies were included. These studies used the levels of the participants' prior knowledge (#3, #17, #31), expertise (#12), spatial abilities (#4) or cognitive styles (#30) as the criterion for splitting them into some categorized groups (such as higher/lower prior knowledge), and aimed to compare the differences in learning behaviors or performances of the participants in the different groups. Noticeably, some studies in Clusters 1 and 2 also discussed the background effect as one of their research questions. However, since the main research issues of these studies were not the effect of background knowledge, they were not assigned to Cluster 3. Four of the six studies used university students as the participants, while the other two used adult learners and high school students, respectively. The sampling rate of all six eye-trackers used in this cluster ranged from 50Hz to 60Hz. With respect to the eye movement measures, five of the six studies used the temporal measures (such as fixation duration and total reading time) to refer to the length of time and amount of attention that the participants used to process the information. Three of the studies used counting measures (such as number of fixations and inter-scanning count) to reveal how the participants allocated their visual attention and how they devoted their mental efforts to integrating information from different sources. Two of the studies used spatial measures (such as scan paths) to identify the patterns of the participants' visual transitions as a way of exploring their cognitive strategies.

In general, the findings of these six studies confirmed the relationships between some personal factors and eye-movement measures. Participants with higher prior knowledge were more likely to spend more time reading both keywords and graphics, and to make more transitions both between graphics and text and between different graphics (#3, #17, #31). When solving spatial problems, learners with higher spatial test performance displayed better working memory and employed more of the analytic strategies (i.e., more analytic eye movements were found) to solve the problems (#4). In the study on transfer of expertise (#12), it was found that experts allocated their attention to task-relevant areas, indicating success of transfer depending on the similarity of the tasks. As for cognitive style, subjects who were identified as imagers fixated more on images, verbalizers on text, and intermediates equally on images and text. Moreover, a match between cognitive style and learning environment improved information processing (#30). In sum, the above findings suggest that eye movement measures reveal the effects of background knowledge, expertise, cognitive ability and style on information processing behaviors.

Cluster 4 - Effects of instructional design on multimedia learning

The theme of Cluster 4 including eight studies emphasized the effects of instructional design on learning outcomes. Most of the studies examined the effectiveness of the uses of the multimedia learning materials which provided visual guides for learners' attention while learning (#5, #11, #25, #27, #29). The manipulations of the design included the use of attentional guide cues (#5), pictures with color coding (#29), text with labeled pictures (#11), illustrations with changing colors for signaling (#27) and different presentation speeds of animation (#25). Regarding the other three studies, one examined the use of expert videos for surgeon skill training (#1), another investigated the impacts of different task demands for concept learning (#10), and the other probed the interaction between different types of graphical representations and uses of learning aids (i.e., uses of additional questions to organize and process information) (#32). Research topics in this cluster included conceptual development and skill learning. Both remote and mobile eye-trackers with sampling rates ranging from 30Hz to 250Hz were utilized in these studies. Almost all of the participants were undergraduate students, except for one study (#11) which involved elementary school students and one (#1) which targeted adult learners. Temporal, spatial and frequency eye-tracking measures were all shown in these studies in which total fixation duration and inter-scanning count were the most commonly used indices for uncovering learners' visual attention distributions and transfers among different instructional elements.

The findings of the studies in this cluster mainly supported the design of visual cues or learning aids to guide students' attention while learning with the multimedia materials. Eye-tracking analyses provided evidence that labeled or signaled pictures significantly promoted the integration of text and graphic comprehension, and therefore enhanced learning outcomes. Cueing was also demonstrated to enhance the effectiveness and efficiencies of learners' visual searches for information relevant to the learning goals. Noticeably, the use of learning aids to support learning increased when subjects read the dynamic graphics (i.e., animations) (#32). Studies in this cluster also demonstrated the effectiveness of the reasoning task with a prediction requirement (#10) and the surgical training program using expert videos (#1). However, it is worth noting that, while manipulating the presentation speed of animation, eye movements seemed to be primarily affected by the learning content rather than by the presentation speed (#25). Eye-tracking evidence also showed the different patterns of eye movements between the groups with different learning outcomes. For example, the learners who were asked to generate predictions were found to focus more on the macroscopic video and make fewer visual transfers between the micro and the macro displays (#10). Meanwhile, longer quite-eye duration and fewer fixations were associated with better performance and more efficient visual strategies for learning surgical skills (#1).

Cluster 5 - Learning with dynamic e-platforms

The papers in Cluster 5 focused on exploring learning in dynamic digital environments in which mobile devices, interactive and collaborative software platforms, and Virtual Reality (VR) technology were employed. There are four papers in this cluster. The main participants were undergraduate and graduate students, and the sampling rate of the eye-trackers used in this cluster was either 50Hz or 60Hz. One study compared learning with desktop computers and mobile devices (#6). Another examined note-taking behaviors (with or without automatic annotation links) in the Interactive Shared Education Environment (ISEE) which supports collaborative video-based distance learning (#22). Two studies designed and employed VR learning environments (#23, #33) and discussed how familiarity and time spent with the environments may affect visual attention. Three of these papers (#6, #22, #23) dealt with learners' conceptual development, while the other (#33) investigated perceptual learning mechanisms.

The major findings are described as follows. First of all, the use of PCs and tablets was found to be more adequate for learning than mobile phones as the use of mobile phones seemed to impose extraneous cognitive load (#6). Secondly, with the help of automatic annotation links, learners were able to attend more to the video content and annotations than to the video control operations (#22). When learners were familiar with the VR learning environments, they became more sensible to the changes of learning objects (#23). Finally, perception learning as indicated by the decrease in fixation numbers was detected when the exposure time to the VR environments changed (#33). The above-mentioned findings imply the adaptability of human learning. In sum, the studies in the cluster suggest that the above-mentioned digital devices, the online platform and VR settings might result in extraneous cognitive loads for users. In addition, familiarity or experience with the new digital devices or VR environments was found to mediate the cognitive activities engaged in the learning task.

In sum, the empirical findings of these eye movement studies provide evidence-based information that can guide the instructional design of science learning in digital environments. Based on the findings of theme cluster, we propose instructional suggestions as listed Table 1 for the design of science learning instruction in digital environments.

Instructional suggestions drawn from study findings

In Table 1, three aspects of instructional design are presented, including the basic design, dynamic environments and individual differences. The study findings of Clusters 1, 2 and 4, contributed to suggestions for the basic design. In cluster 1, it was found that learners, when reading science learning materials, attended more to verbal areas when text and graphics were presented together. When graphics contained conceptual information, the reading time of the graphics increased. The integration of verbal and visual information (indicated by the inter-scanning between text and graphics) was found to be the most significant predictor of conceptual achievement. While animations are able to depict complex phenomena or processes, they might produce extraneous cognitive load. The studies in Cluster 2 confirmed mostly the multimedia effects such as the multimedia representation effect, the coherence effect, the contiguity effect and the modality effect, but the coherence effect was not conclusive. It was shown that irrelevant illustrations in science texts moderated the beneficial effect of instructional pictures more specifically for learners with low prior knowledge. In addition, the processing time of animations predicted learning outcomes. The findings in Cluster 4 showed that visual cueing or labeled pictures enhanced learners' attention and promoted information integration, and that learners' visual attention and reasoning performance can be changed and improved by a prediction task. The later finding suggests that task-relevant activities given before the main learning event affect the allocation of learners' cognitive resources.

Based on the above-mentioned findings, it is recommended that the basic design of the digital instruction for science learning should follow the design principles suggested by the theory of multimedia learning, such as placing related text and graphics near each other and employing only one type of verbal mode of information (either written or spoken). The verbal explanations should be carefully written to uncover explicitly the conceptual knowledge embedded in the graphical information. To help science learners to effectively integrate relevant information, instructional guidance encouraging back and forth scanning between different representations should be provided. In addition, effective use of visual cueing or labeled pictures will enhance learners' attention and promote information integration. Giving learners a prediction task prior to the learning task will affect the allocation of learners' cognitive resources and enhance learning performance. As far as the use of animations is concerned, since it has been reported that animations may cause extraneous cognitive load and require more time to be processed in depth, additional instruction or explanation of the goal and content of the animation needs to be given to guide learners' attention.

Table 1. Instructional suggestions drawn from the findings of eye-tracking studies

Design aspects	Features	Major eye movement findings (Cluster#)	Instructional suggestions
Basic design	Verbal mode + visual mode	• Readers attend more to the written texts than to the graphics. (C1) • Verbal information guides visual attention (C1) • When the graphics are in conceptual, sequential or interactive form, the visual attention and processing time of the target areas increases (C1) • Transitions between different presentation modes predict concept achievement (C1) • An overview of the graphic helps to establish mental scaffolding for text reading (C1) • Visualizations were processed more when coupled with spoken texts than written texts (C2) • Irrelevant illustrations (either text or graphic) might hinder retention (C2) • Labeled or signaled pictures promote the integration of text and graphic comprehension (C4) • Cueing enhances the effectiveness and efficiencies of learners' visual search for the relevant information (C4) • Reasoning tasks with a prediction requirement enhance performance (C4)	• Related text and graphics should be placed near each other (contiguity effect) • Use one verbal mode at a time (either written text or spoken text) (modality effect) • Learners rely heavily on written information to construct their conceptual models. Therefore, verbal explanations should be carefully written to explicitly uncover the conceptual knowledge embedded in the graphical information • When graphics contain conceptual information or are in sequential or interactive form, additional guidance or instruction that directs learners' attention and processing time of such graphics is critical • Giving instructional guidance encouraging back and forth scanning between different representations will help information integration • Use labels, cues or questions to guide and encourage back and forth reading • Place learners in a learning context that requires them to reason and make predictions
	Verbal mode + dynamic visual mode *(Animation, video)*	• Animations may result in extraneous cognitive load and require more time to process (C1) • Questions that help to organize and process information promote animation reading (C4)	• Allow self-paced timing of the reading of animations • Explicit explanations of the goals or contents of animations are necessary to reduce the extraneous cognitive load • Use organizer questions to help meaning construction, such as: • What is important about the statement? • How is the demonstration related to the topic to be learned? • How are different concepts/ideas related? • (*Note.* The above questions are adopted from Ruf & Ploetzner, 2014)
Dynamic environments	Verbal mode + visual mode (*Learning with mobile devices or in a VR environment*)	• Learning in PC environments is more efficient than on mobile devices which seem to impose extraneous cognitive loads (C5) • In the video environment, annotation links help attention allocations (C5) • Familiarity and prior experiences	• To enhance the effectiveness of the dynamic and interactive learning platforms, some preparation or training sections are necessary for learners to become familiar with the new devices or settings

		with the new learning platforms (including mobile devices and the VR setting) determine the success of learning. (C5)	
Individual differences	Background knowledge	• Background knowledge helps to reduce processing time (C1) • Learners with a strong background spend more time reading both keywords and graphics, and make more transitions between graphics and text (C3) • Decorative pictures moderate the beneficial effect for learners with lower prior knowledge (C2) • Learners with low prior knowledge need more coherent multimedia instruction (C2)	• Detection of learners' prior knowledge is necessary to give adaptive instruction • Learners with lower prior knowledge need visual guides or cues to guide their attention • For learners with lower prior knowledge, avoid irrelevant illustrations and provide highly coherent instruction.
	Cognitive abilities	• Learners with higher spatial test performance display better working memory and employ more analytic strategies (C3)	• Learners with lower spatial test performance would need learning aids that can show the result of spatial manipulations in mind to support their working memory • A training program introducing the analytic strategies for solving the spatial related problem should be helpful for learners with lower spatial performance.
	Cognitive styles	• Subjects identified as imagers fixate more on images, verbalizers on text, and intermediates equally on images and text (C3) • Environments that match learners' cognitive styles seem to enhance learning results (C3)	• Adopt different design approaches. For example, more visual representations should be used for imagers, while more verbal explanations may benefit verbalizers. • An instruction or guidance that can direct the attention of imagers/verbalizers to verbal/visual areas respectively, will be necessary to enhance the process of information integration

The dynamic digital environments are characterized by the use of mobile devices, interactive software platforms, or VR technology. These digital technologies have been developed in recent years, and therefore their effectiveness, when they are used to support multimedia learning, needs further evaluation. The studies in Cluster 5 addressed this issue. It was shown that although these digital environments have unique features such as portability, user-controlled interaction, and replication of an environment that simulates a physical presence in places in the real world, the use of these newly developed learning environments might result in extraneous cognitive load. Some studies in Cluster 5 found that experiences and familiarity with the new technologies affect cognitive activities. Accordingly, additional preparation or pre-task training programs are favored in order to enhance learners' familiarity with the environmental settings while also reducing extraneous cognitive load.

The last aspect of the instructional suggestions is individual differences. As discussed in Cluster 3, individuals with different knowledge backgrounds, cognitive styles and spatial performances displayed different eye movement patterns, indicating a close link between visual attention and information processing strategies. The findings of these studies provide empirical information that can be used to develop adaptive instruction. For example, those who had better background knowledge were more able to allocate their visual attention to key areas in the science learning materials. Accordingly, visual guides or cues should be provided especially for science learners with lower prior knowledge so that they can allocate their attention and time more efficiently to the target areas or activities. Learners with lower spatial test performance would need learning aids that can show visually the result of spatial manipulations in mind to support their working memory. This can be achieved by the design of interactive programs allowing learners to display their mental work. In addition, these learners might need additional training to develop appropriate analytic strategies such as selecting, comparing, matching, orienting and so forth for solving spatial related problems. For students who are identified as imagers/verbalizers who look more at images/text, instruction or guidance that can direct their attention to verbal/visual areas, it will be necessary to enhance the process of information integration. Noticeably, although background knowledge was not the main issue addressed in Clusters 1 and 2, several studies in the two clusters addressed the issue as one of their research questions. In general, higher background knowledge less processing time. In short, the eye movement studies addressing individual differences have confirmed that attention distributions and the speed of information processing are affected by cognitive factors and prior knowledge. Accordingly, instructors should identify first these characteristics that their learners possess, and make use of the characteristics to develop adaptive instructions.

In conclusion, our analysis on the themes of the selected papers suggested that the design of e-learning instruction should consider placing related text and graphics in adjacent areas, using one verbal mode at a time, providing explicit and clear verbal explanations, and explaining carefully the goals and contents of the animations to reduce the extraneous cognitive load when animations are used. In addition, before students are placed in the dynamic learning environments, the instructor needs to provide a pre-training program allowing students to become familiar with the new environment. Finally, individual differences such as background knowledge, cognitive abilities and cognitive styles should be taken into consideration in the instructional design.

Suggestions for future studies

Based on the findings of this review study, we have proposed some design principles for digital learning as Table 1 shows. In addition to the suggestions for schoolteachers or curriculum instructors, there are many research issues worth of further explorations. As mentioned in the "general characteristics of the reviewed papers," it was evident that most of these studies recruited adult students, which might limit applications of the instructional suggestions. To understand more of learners' characteristics and development trajectories, future studies should involve younger science students, such as elementary students or even preschoolers. While eye movement measures have successfully demonstrated that differences in prior knowledge or expertise, cognitive ability or style would result in variations in information processing strategies, the studies on individual differences have not been sufficiently accumulated to be conclusive. It is thus expected that more eye-tracking studies be devoted to examining the personal factors such as cognitive ability, learning style and personal values. As discussed in several papers reviewed in the study, science learning performances were influenced by experiences and familiarity with the multimedia learning environments. Since science learning performance is also mediated by personal factors such as background knowledge, cognitive ability, and learning style as discussed in the study, another research agenda in the future should be the testing of the effectiveness of adaptive instructional designs, taking into consideration personal factors, and exploring the patterns of eye movements associated with better learning outcomes. These patterns may serve as references for providing individual feedback in the adapted learning systems.

In addition to the learner characteristics and cognitive factors, future research attention should be also placed to the learning topics and the teaching/learning materials. As mentioned in the overall results, the learning topics explored by the reviewed papers focused largely on conceptual developments. Topics such as skill learning and reasoning which have attracted educators' attention in recent years deserve more research efforts. Among the reviewed papers, most of them used static images as their experimental materials, with only a few exceptions. Given that dynamic images or graphics are becoming a popular form of multimedia representation in science teaching and learning, more studies should be conducted to test their effects on learning. However, since tracking a dynamic AOI (such as a video or simulation) is complex and time consuming, it might need further collaboration with software or image-processing developers to analyze the eye movement data.

A review study written by Hsu et al. (2012) has shown that a growing research in the technology-based learning concerns issues regarding pedagogical design the development and evaluation of new learning systems, platforms and architectures. With the rapid development in media or visualization technologies such as augmented reality (AR) and VR technologies, dynamic learning environments have been created. By tracking eye and head movements in an immersion environment, it becomes possible to monitor the perceivers' relation with virtual objects' spatial characteristics (Renaud et al., 2003). Therefore, the last recommendation for the future work is the call for more eye tracking studies examining the effectiveness of learning in the new digital learning environments, in particular the dynamic types such as the mobile devices, AR and VR environments which have been developed and taken notice of only in recent years. To study the dynamic digital learning environments, the mobile types of eye trackers are preferred. Nevertheless, the software that can effectively analyze the eye movements in moving areas of interest is still premature. The collaboration between software engineering and education researchers is thus necessary to optimize the eye tracking method.

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Appendix

Table 2. List of reviewed article papers

N	Title	Author	Journal information	Learning topics	Subjects	Eye movement measures	Performance measures
1	Quiet eye training improves surgical knot tying more than traditional technical training: a randomized controlled study	Causer, J. Harvey, A., Frcs, Snelgrove, R., Arsenault, G. & Vickers, J. N. (2014).	The American Journal of Surgery, 208, 171-177	Skill learning	1st-year surgical residents	1. Percentage of fixation duration 2. Number of fixations 3. Movement time	1. Knot tying performance 2. Performance time
2	Learning from multiple representations: An examination of fixation patterns in a science simulation	O'Keefe, P. A., Letourneau, S. M., Homer, B. D., Schwartz, R. N., & Plass, J. L. (2014).	Computers in Human Behaviors, 35, 234-242	Conceptual development	High school students	1. Number of fixations 2. Total fixation time 3. Eye transitions	Multiple-choice knowledge tests
3	Prior knowledge and online inquiry-based science reading: Evidence from eye tracking	Ho, H. N. J., Tsai, M. J., Wang, C. Y., & Tsai, C. C. (2014).	International Journal of Science & Mathematics Education, 12, 525-554	Conceptual development	University and graduate students	1. Total reading time 2. Total fixation duration 3. Total regression number 4. Inter-scanning counts	Paper-and-pencil knowledge test
4	Probing the relationship between process of spatial problems solving and science learning: An eye tracking approach	Chen, Y. C. & Yang, F. Y. (2014)	International Journal of Science & Mathematics Education, 12, 579-603	Conceptual development & skill learning	University students	1. Total fixation duration 2. Average fixation duration 3. Percentage of total fixation duration 4. Number of regressions	1. PVRT performance test 2. Concept test 3. Responses to interview questions re problem solving strategies
5	An eye-tracking study of cueing effects in multimedia learning	Jamet, E. (2014)	Computers in Human Behaviors, 32, 47-53	Conceptual development	University students	1. Mean fixation time 2. Number of gaze shifts	Paper-and-pencil knowledge tests
6	Assessing the	Molina, A. I,	Computers	Conceptual	Adult &	1. Scan	1. Concept test

	effectiveness of new devices for accessing learning materials: An empirical analysis based on eye tracking and learner subjective perception	Redondo, M. A., Lacave, C., & Ortega, M. (2014).	in Human Behavior, 31, 475-490	developme nt	university students	paths 2. Fixation duration	2. Perception questionnaire s for technology acceptance, cognitive load, and motivation
7	Seductive details and attention distraction – An eye tracker experiment	Rey, G. D. (2014)	Computers in Human Behavior, 32, 133-144	Conceptual Developme nt	55 university students	1. Mean total fixation time 2. Total reading time 3. Anti-saccade	Knowledge tests (retention & transfer)
8	The role of decorative pictures in learning	Lenzner, A., Schnotz, W., & Muller, A. (2013)	Instructional Science, 41, 811-831	Perception	7th and 8th graders	1. Gaze duration 2. Number of switches between text and picture 3. Time of the first visit	N/A
9	How Inspecting a Picture Affects Processing of Text in Multimedia Learning	Eitel, A., Scheiter, K, & Schuler, A. (2013)	Applied Cognitive Psychology, 27, 451-461	Conceptual developme nt	University students	Dwell times (reading times)	1. Verbal recalls 2. Comprehensi on tests
10	When do spatial abilities support student comprehensio n of STEM visualizations ?	Hinze, S. R., Williamson, V. M., Shultz, Williamson, M. J., Wiliamson, K. C., Deslongcham ps, G., & Rapp, D. N. (2013)	Cognitive Process, 14, 129-142	Conceptual developme nt	University students	1. Total fixation duration 2. Proportio n of fixation duration 3. Transitio ns between animatio ns and videos	1. Four tests for assessing spatial ability 2. Comprehensi on tests
11	Effects of Picture Labeling on Science Text Processing and Learning:	Mason, L. Pluchino, P., & Tornatora, M. C. (2013)	Reading Research Quarterly, 48, 199-214	Conceptual developme nt	Sixth graders	1. First-pass fixation time 2. Second-pass fixation	1. Comprehensi on test (pre, post, delayed-post) 2. Spatial ability tests

	Evidence From Eye Movements					times (look-from)	3. Working Memory tests 4. Achievement records
12	Transfer of expertise: An eye tracking and think aloud study using dynamic medical visualizations	Gegenfurtner, A., & Seppanen, M. (2013)	Computers & Education, 63, 393-403	Skill learning	Medical professionals	1. Number of fixations 2. Fixation durations	1. Diagnostic performance 2. Verbal reports about task engagement
13	Tracking learners' visual attention during a multimedia presentation in a real classroom	Yang, F. Y., Chang, C. Y., Chien, W. R., Chien, Y. T., & Tseng, Y. H. (2013)	Computers & Education, 62, 208-220	Conceptual development	University students	1. Total fixation duration 2. Number of fixations 3. Average fixation duration 4. Percentage of viewing time 5. Percentage of total fixation 6. Frequency of saccade path	Concept recall
14	Identifying student use of ball-and-stick images versus electrostatic potential map images via eye tracking	Williamson, V. M., Hegarty, M., Deslongchamps, G., Williamson, K. C., & Shultz, M. J. (2013)	Journal of Chemical Education, 90, 159-164	Conceptual development	University students	1. Number of fixations 2. Total fixation time	Responses to interview questions
15	An eye movement analysis of the spatial contiguity effect in multimedia learning	Johnson, C. I. & Mayer, R. E. (2012)	Journal of Experimental Psychology-Applied, 18, 178-191	Conceptual development	College students	1. Text-to-diagram transitions 2. Proportion of transitions 3. Proportion of fixations 4. Total fixation durations	1. Spatial ability 2. Retention and transfer tests.
16	Effects of different multimedia	Chuang, H. H. & Liu, H. C. (2012)	Journal Of Science Education	Conceptual development	College students	1. Number of fixations	N/A

	presentations on viewers' information-processing activities measured by eye-tracking technology		And Technology, 21, 276-286			2. Total fixation duration 3. Pupil size 4. Scan path	
17	Visual attention for solving multiple-choice science problem: An eye-tracking analysis	Tsai, M. J., Hou, H. T., Lai, M. L., Liu, W. Y., & Yang, F. Y. (2012)	Computers & Education, 58, 375-385	Conceptual developme nt	College students	Fixation durations	1. Problem solving performance (think aloud) 2. Computer log records (typing and mouse clicking)
18	Using eye-tracking technology to investigate the redundant effect of multimedia web pages on viewers' cognitive processes	Liu, H. C., Lai, M. L., & Chuang, H. H. (2011)	Computers In Human Behavior, 27, 2410-2417	Conceptual developme nt	Male university students	1. Number of fixations 2. Fixation duration 3. Saccades 4. Scan path 5. Pupil dilation	Cognitive load
19	The influence of different representatio ns on solving concentration problems at elementary school	Liu C. -J., & Shen M.-H. (2011)	Journal Of Science Education And Technology, 20, 621-629	Skill/strate gy learning	Third and fifth grade students	1. Fixation duration 2. Saccade duration 3. Blink duration	Correct rate
20	Identifying representatio nal competence with multi-representatio nal displays	Stieff M., Hegarty M., & Deslongcham ps G. (2011)	Cognition And Instruction, 29(1), 123-145	Conceptual developme nt	University students	1. Total fixation duration 2. Saccades (transitio ns)	1. Accuracy rate 2. Verbal responses 3. Interaction with animations
21	An examination of cognitive processing of multimedia information based on viewers' eye movements	Liu H. -C., & Chuang H. -H. (2011)	Interactive Learning Environmen ts, 19(5), 503-517	Conceptual developme nt	University students	1. Number of fixations 2. Fixation duration 3. Location of fixation 4. Fixation density saccade 5. Number of saccades 6. Saccade length	N/A
22	Towards	Mu, X. (2010)	Computers	Skill/strate	60	1. Reading	1. Average

	effective video annotation: An approach to automatically link notes with video content		& Education, 55, 1752-1763	gy (note taking)	university students	time 2. Gaze movements	length of notes 2. Total number of annotations 3. Distribution of note-taking frequencies 4. Clicks on links
23	Change detection in desktop virtual environments: An eye-tracking study	Karacan, H., Cagiltay, K., Tekman, H. G. (2010)	Computers In Human Behavior, 26, 1305-1313	Perception	University students	1. Total fixation duration 2. Average fixation duration 3. Location of fixation	Response time
24	A closer look at split visual attention in system- and self paced instruction in multimedia learning	Schmidt-Weigand, F. Kohnert, A., & Glowalla, U. (2010)	Learning And Instruction, 20, 100-110	Conceptual development	University students	1. Total viewing time 2. Number of transitions between text and visualizations	1. Test for experience with meteorology 2. Retention and transfer test 3. Visual memory test.
25	Effects of animation's speed of presentation on perceptual processing and learning	Meyer, K., Rasch, T., Schnotz, W. (2010)	Learning And Instruction, 20, 135-145	Conceptual development	University students	Proportions of fixation time	1. Prior knowledge test 2. Comprehension test
26	Explaining the Modality and Contiguity Effects: New Insights From Investigating Students' Viewing Behavior	Schmidt-Weigand, F. Kohnert, A., & Glowalla, U. (2010)	Applied Cognitive Psychology, 24, 226-237	Conceptual development	University students	Total viewing time	1. Prior knowledge test 2. Retention and transfer test
27	Why does signaling enhance multimedia learning? Evidence from eye movements	Ozcelik, F., Arslan-Ari, I., Cagiltay, K. (2010)	Computers In Human Behavior, 26, 110-117	Conceptual development	University students	Fixation duration and location	1. Prior knowledge test 2. Retention and transfer test 3. Matching test
28	The impact of multimedia effect on science	Hsiao-Ching She, Yi-Zen Chen (2009)	Computers & Education, 53, 1297-	Conceptual development (mitosis and	24 7th grade students (average	number of fixations, total inspection	pre-test, post-test (understanding of mitosis and

	learning: Evidence from eye movements		1307	meiosis)	age 12 yrs)	time, mean fixation duration	meiosis), and retention-test scores
29	An eye-tracking study of how color coding affects multimedia learning	Ozcelik, E. Karakus, T. Kursun, E. & Cagiltay, K. (2009)	Computers & Education, 53, 445-453	Conceptual development	University students	Total fixation time	1. Prior knowledge test 2. A subjective rating scale for perceived difficulty 3. Retention test
30	An experimental assessment of the use of cognitive and affective factors in adaptive educational hypermedia	Tsianos, N., Lekkas, Z., Germanakos, P., Mourlas, C., Samaras, G. (2009)	IEEE Transactions On Learning Technologies, 2(3), 249-258	Conceptual development	University students	1. Number of fixations 2. Fixation duration 3. Scan path	1. Cognitive Style Analysis 2. Visuospatial working memory span test (VWMS) 3. Speed and accuracy task-based tests 4. Anxiety tests 5. Comprehension test
31	The influence of prior knowledge on viewing and interpreting graphics with macroscopic and molecular representations	Cook, M., & E., W. G. Carter (2008)	Science Education, 848-867	Conceptual development	High school students	Sequential path analysis of fixation	1. Prior knowledge assessment 2. Comprehension interview
32	One click away is too far! How the presentation of cognitive learning aids influences their use in multimedia learning environments	Ruf, T., & Ploetzner, R. (2014)	Computers in Human behavior, 229-239	Conceptual Development	University students	1. Fixation counts 2. Fixation sequence saccade (alternating between reading and in the support and content areas)	1. Posttest on factual knowledge 2. Transfer test
33	What does germane load mean? An empirical contribution to the cognitive	Debue, N. & van de Leemput, C. (2014)	Frontiers in psychology, v. 5, 1-12	Conceptual development	University students	1. Mean number of fixations 2. Fixation duration 3. Saccade	Content recalls

load theory	velocity 4. Pupil diameter