Volume 10, December 2013   ISSN 1747-938X

Educational Research REVIEW

Editor-in-Chief
Päivi Tynjälä, *University of Jyväskylä, Finland*

Earli
An official Journal
of The European
Association for
Research on
Learning and
Instruction

Associate Editors
David Gijbels, *University of Antwerp, Belgium*
Ming-fai Pang, *University of Hong Kong, China*
Keith Sawyer, *Washington University, USA*
Helen Watt, *Monash University, Australia*

Review

A review of using eye-tracking technology in exploring learning from 2000 to 2012

Meng-Lung Lai [a], Meng-Jung Tsai [b], Fang-Ying Yang [c,*], Chung-Yuan Hsu [d], Tzu-Chien Liu [e], Silvia Wen-Yu Lee [f], Min-Hsien Lee [g], Guo-Li Chiou [h], Jyh-Chong Liang [b], Chin-Chung Tsai [b]

[a] National Chiayi University, No. 85, Wenlong, Minhsiung, Chiayi County 621, Taiwan
[b] National Taiwan University of Science and Technology, No. 43, Sec. 4, Keelung Rd., Da'an Dist., Taipei City 106, Taiwan
[c] National Taiwan Normal University, No. 88, Sec. 4, Ting-Zhou Rd., Wen-Shan Dist., Taipei City 116, Taiwan
[d] National Pingtung University of Science and Technology, No. 1, Shuefu Road, Neipu, Pingtung 912, Taiwan
[e] National Central University, No. 300, Jhongda Rd., Jhongli City, Taoyuan County 320, Taiwan
[f] National Changhua University of Education, No. 1, Jin-De Road, Changhua City, Taiwan
[g] National Sun Yat-Sen University, No. 70, Lienhai Rd., Kaohsiung City 80424, Taiwan
[h] National Chiao Tung University, No. 1001, University Road, Hsinchu City 300, Taiwan

ARTICLE INFO

ABSTRACT

This study aims to disclose how eye-tracking technology has been applied to studies of learning, and what eye movement measures have been used for investigations by reviewing studies that have employed the eye-tracking approach. A total of 81 papers including 113 studies were selected from the Social Sciences Citation Index database from 2000 to 2012. Content analysis showed that eye movements and learning were studied under the following seven themes: patterns of information processing, effects of instructional design, reexamination of existing theories, individual differences, effects of learning strategies, patterns of decision making, and conceptual development. As for eye-tracking measurements, the most often used indices were temporal measures, followed by count and spatial measures, although the choice of measures was often motivated by the specific research question. Research development trends show that the use of the eye-tracking method has proliferated recently. This study concludes that the eye-tracking method provides a promising channel for educational researchers to connect learning outcomes to cognitive processes.

Contents

* Corresponding author. Address: Graduate Institute of Science Education, National Taiwan Normal University, No. 88, Sec. 4, Ting-Zhou Rd., Taipei 116, Taiwan. Tel.: +886 2 77346801; fax: +886 2 29327630.
E-mail address: fangyang@ntnu.edu.tw (F.-Y. Yang).

1. Introduction

In educational research, a considerable number of studies have been devoted to the processes and outcomes of learning (e.g., Posner, Strike, Hewson, & Gertzog, 1982; Schnotz, Vosniadou, & Carretero, 1999). Traditionally, the interview procedure based on the think-aloud protocol has been the most important and frequently used technique to probe cognitive activities during learning (LeCompte & Preissle, 1993; Mintzes, Wandersee, & Novak, 1999). However, such a method often suffers from validity issues. For this reason, educational researchers are seeking various research methods developed in different academic domains in the hope of presenting the process of learning from different angles (Anderson, 2007). Among various techniques, the eye tracking method, which has been intensively used by psychologists to study basic cognitive processes during reading and other types of information processing (Rayner, 1998, 2009), has just started to attract attention from educators in recent years. This method is valuable due to its capacity to recode online cognitive activities, and therefore, it is certainly a promising tool for tracking the cognitive process of learning.

As mentioned, the use of eye tracking technology in educational research has been growing in recent years, but most studies have been conducted in psychology related fields. Consequently, what learning issues have been explored by the technology, and how different eye movement measures can inform us about cognitive activities during learning are still not easily assessable by educators. A systematic analysis of the eye movement studies related to learning would allow educators to better understand how the eye tracking technology could be and has been used. Therefore, in the current work, by carrying out an extensive literature review, we have made an attempt to examine how the eye movement studies in psychology are related to studies of learning in the domain of education. A bridging framework is then established to illustrate the relationship.

2. Literature review

2.1. Learning & cognitive development

The paradigm shifts in the theories of learning, moving from behaviorism emphasizing observable behaviors to cognitive perspectives embracing mental activities, have had a tremendous influence on educational practice. Early cognitive psychologists such as Piaget and Vygotsky proposed that cognitive development undergoes active changes in cognitive structures. Based on such a viewpoint, learning is thought to bring about cognitive development (e.g., Ginsburg & Opper, 1988; Phillips & Soltis, 2009). The cognitive position on learning is further strengthened by many modern neurocognitive studies showing the flexibility of the human brain, and the effect of learning on the change in brain structure (e.g., Galván, 2010; Goswami, 2008; Lee et al., 2010). In sum, supported by both cognitive and neurocognitive studies, learning manifests itself in not only the acquisition of new information, but also the development of perception, social cognition, language, mathematical thinking, causal/scientific reasoning, psychomotor skills, problem solving skills and strategies, and conceptual knowledge (Anderson, 2009; Goswami, 2008). Accordingly, when learning becomes a subject to be examined, one may find that the foci of discussions are actually related to different aspects of human cognitive development. For that reason, the topics of learning discussed in this review study include various aspects of cognitive development as defined previously.

2.2. Eye movement applications

People's visual perception typically consists of three parts: foveal, parafoveal, and peripheral vision. The fovea is the central area of the retina; the parafovea describes the region surrounding the fovea; and the periphery refers to the region outside the parafovea. Acuity is greatest in the fovea, decreasing in the parafovea, and is even poorer in the periphery. In order to see things clearly, people frequently move their eyes to locate objects of interest in the region of greatest visual resolution (fovea) (Liversedge, Gilchrist, & Everling, 2011). Eye movement researchers have identified different types of eye movement, some of which keep the fovea on a visual target in the environment (e.g., saccades and smooth pursuits), while others stabilize the eye during head movement (e.g., fixations) (Duchowski, 2007; Liversedge et al., 2011; Underwood & Radach, 1998). Studies have shown that different readers have different perceptual spans indicating areas of effective vision, and that new information is not acquired during saccades (Rayner, 1986, 1998).

The eye tracking method is basically developed based on the abovementioned characteristics of eye movements and the "eye-mind" assumption proposed by Just and Carpenter (1980), which suggests that eye movements provide a dynamic trace of where attention is being directed. Although there are studies showing inconsistent results, it is widely agreed that during a complex information processing task such as reading, eye movements and attention are linked (Rayner, 1998).

As mentioned previously, the eye-tracking method has been successfully and broadly applied to research in psychology related fields for decades. Most applications are related to research involving information processing, such as reading, scene perception, visual searching, music reading, and typing (for a detailed review see Radach & Kennedy, 2004; Rayner, 1998, 2009). Measures of eye movements have revealed the fundamental cognitive processes and mechanisms involved in reading comprehension (Rayner, Chace, Slattery, & Ashby, 2006) and visual perception (Liversedge & Findlay, 2000). On the other hand, eye tracking techniques have also been applied to investigate human–computer interactions (Goldberg & Helfman, 2011; Jacob & Karn, 2003) as well as media communications (Hyönä, 2003). As for high level cognitive processing, some prior studies have attempted to utilize eye trackers for examinations such as exploring the process of arithmetic problem solving (e.g., Hegarty, Mayer, & Green, 1992). Recently, some researchers have even used this technique to explore learning processes in complex learning contexts such as emergent literacy, multimedia learning, and science problem solving strategies (e.g., Tsai, Hou, Lai, Liu, & Yang, 2012; van Gog & Scheiter, 2010). Readers may find comprehensive overviews of the eye tracking methods and practices in some recently published books (e.g., Duchowski, 2007; Holmqvist et al., 2011; Liversedge et al., 2011). It seems that eye-tracking techniques could be employed in different ways for different studies; therefore, a conceptual framework of eye-tracking measures is important for educational researchers to conduct eye-tracking studies. In sum, before integrating eye-tracking techniques into educational studies, educational researchers need to know what eye-tracking measures are typically used and how they have been used in the related literature.

2.3. Eye movement measures

In general, eye movements consist of a series of fixations and saccades while reading information or viewing scenes. Psychological and human–computer-interaction studies usually define a fixation as a relatively stable state of eye movement, and a saccade as the rapid eye movement between two consecutive fixations. According to Rayner (1998, 2009), a fixation generally ranges from 100 to 500 ms, depending on the viewed materials. A fixation is, on average, about 250 ms while reading. A 2-degree saccade usually takes about 30 ms in a typical reading task, while a 5-degree saccade (typical of scene perception) lasts about 40–50 ms. Many different eye-tracking measures have been used in prior studies and most of the measures focus on reading or word-based contexts.

Eye-tracking measures have been conceptualized in different approaches. Liversedge, Paterson, and Pickering (1998) illustrated the use of reading time measures and provided a thorough discussion of temporal measures versus spatial measures. Goldberg and Kotval (1999) evaluated several spatial measures based on eye movement locations and scanpaths for computer interface evaluation. Jacob and Karn (2003) then reviewed 21 usability studies incorporating eye-tracking techniques, and summarized six frequently used eye-tracking measures as *fixation count, proportion of time spent on each area of interest (AOI), average fixation duration, fixation count on each AOI, gaze duration mean on each AOI, and fixation rate (count/s).* Meanwhile, according to the scale of measurement, Radach and Kennedy (2004) grouped word-based eye-tracking measures into two categories: a *temporal* scale (measured by time) and a *spatial* scale (measured by space).

To systematically understand eye movement measures, the current study summarized commonly used eye-tracking indices according to two dimensions (shown in Table 1): *types of eye movement* (*fixation, saccade, mixed*) and *scales of measurement* (*temporal, spatial, count*). Each of the eye-tracking measures is briefly defined in Table 2. Of the three types of eye movement, fixation and saccade are the two major types recorded by eye-trackers and defined in the above section. The mixed type, indicating a combination of fixations and/or saccades, is considered and analyzed, e.g., *total reading time* which includes both fixation durations and saccade durations, and *scanpath* which consists of multiple successive fixations and saccades.

Regarding the scales of measurement, three categories can be identified: *temporal, spatial* and *count.* First, the temporal scale means that eye movement is measured in a time dimension, e.g. durations of time spent on some particular areas of interest. Several common eye-tracking indices such as total fixation duration, total reading time and time to first fixation are measured in this scale. Another index commonly used in reading research is *gaze duration* which refers to the total fixation

Table 1
Commonly used eye-tracking measures in a two-dimensional framework.

Fixation	Saccade	Mixed
Temporal		
Total fixation duration	Saccade duration	Total reading time
Gaze duration		First pass time
Average fixation duration		Re-reading time
First fixation duration		
Time to first fixation		
Revisited fixation duration		
Proportion of fixation duration		
Spatial		
Fixation position	Saccade length	Scanpath pattern
Fixation sequence		
Count		
Fixation count	Saccade count	
Average fixation count	Inter-scanning count	
Revisited fixation count		
Probability of fixation count		

Table 2
Definitions of eye-tracking measures.

Measures	Definition
Temporal	
Total fixation duration	Total time spent on fixations
Gaze duration	Total fixation duration within a word or an AOI
Average fixation duration	Mean of fixation duration on each AOI. (i.e., Gaze duration mean)
First fixation duration	Time spent on the first fixation
Time to first fixation	Time spent from stimuli onset to the first fixation arrival
Revisited fixation duration	Sum of revisited fixation durations within an AOI
Proportion of fixation duration	Proportion of time fixated on an AOI compared to the total fixation durations or total reading time of a whole task
Saccade duration	Sum of saccadic time spent within an AOI
Total reading time	Total time spent for a reading task or spent within an AOI
First pass time	Time spent for the first entering of an AOI until leaving
Re-reading time	Sum of revisited time spent within an AOI
Spatial	
Fixation position	Location of a fixation
Fixation sequence	Sequence of fixation allocations on AOIs
Saccade length	Distance between two consecutive fixations
Scanpath pattern	Pattern of fixation sequences
Count	
Total fixation count	Total number of fixations counted in an AOI or in a task
Average fixation count	Average fixation count on each AOI
Revisited fixation count	Sum of revisited fixations count within an AOI
Probability of fixation count	Probability of fixation count within an AOI compared to the number of fixations overall
Saccade count	Total number of saccades counted within an AOI
Inter-scanning count	Number of fixation transactions between AOIs

duration within a word. Temporal measures may answer the "when" and "how long" questions in relation to cognitive processing, and are often used to imply the occurrences of reading problems (Liversedge et al., 1998).

Second, the spatial scale measures eye movement in a space dimension. It concerns locations, distances, directions, sequences, transactions, spatial arrangement or relationships of fixations or saccades. Indices such as fixation position, fixation sequence, saccade length and scanpath patterns belong to this scale. Sometimes, researchers further analyze the directions of saccadic movements by specifying *progressive saccade* or *regressive saccade.* Spatial measures may answer the "where" and "how" questions in relation to cognitive process. Saccadic eye movements and scanning behaviors are important in that they reveal the control of selective processes in visual perceptions including visual searching and reading (Liversedge & Findlay, 2000).

Finally, the count scale measures eye movements on a count or frequency basis. For example, fixation count, revisited fixation count and probability of fixation count belong to this category. These count measures are usually used to reveal the importance of visual materials. Sometimes, fixation counts are strongly correlated with measures such as total fixation duration. This suggests that measurements in different categories might possibly reflect the same cognitive process.

Overall, the above framework provides a basic guideline to understand the various types and characteristics of eye movement measures. However, we should notice that research in different domains may focus on different categories of eye-tracking measurements. For example, reading research may focus more on temporal measures, while visual perception

research may focus more on spatial measures. In addition, a measurement can sometimes be named in different ways depending on the materials and tasks. For example, "total reading time" can be shown as "total viewing time", "total inspection time" or "total trial time." Besides, some relatively newly or controversially developed measures are not included in the above framework, such as pupil dilation and blinks which have been discussed or used to infer users' mental work load in some human–computer-interaction studies (Beatty, 1982; Gilman & Underwood, 2003; Hess & Polt, 1964; Öquist, Hein, Ygge, & Goldstein, 2004). In sum, the eye-tracking technique is an attractive and powerful tool to reveal the cognitive processes of student learning. However, it is a challenge for educators to integrate eye-tracking techniques into educational studies. Educational researchers need to know not only how to employ them as a methodology but also how to apply and interpret their measurements in order to properly understanding student learning processes in varied learning situations.

3. Purpose of the paper

In this study, we review empirical studies that have employed the eye tracking technology to probe the cognitive processes during learning. By analyzing relevant works of the past 13 years (since 2000), we expect to disclose how the eye-movement approach has been applied to the studies of different learning topics, and what eye movement measures have been used for investigation. The analysis and integration of the abovementioned information may help to construct a framework revealing how the eye tracking method can inform us about cognitive activities related to learning.

4. Method

4.1. Paper selection

The literature source for this review was the Social Sciences Citation Index (SSCI) database, one of the highly recognized databases indexing core journals in the social sciences. The time span was set from 2000 to 2012, and the document type was limited to journal articles in an attempt to review studies of potentially more consistent quality. The procedures implemented to identify the research papers of this study can be classified into two stages. In the first stage, four sets of keywords were organized for searches using the Boolean operator 'AND,' including "eye movement∗ AND learning", "eye tracking AND learning", "eye movement∗ AND education", as well as "eye tracking AND education." Subsequently, these four sets of keywords were combined using the Boolean operator 'OR.' When the results were produced, we refined the subject areas to physics, mathematics, behavioral sciences, psychology, developmental psychology, educational psychology, experimental psychology, mathematical psychology, multidisciplinary psychology, education and educational research, and special education.

In the second stage, four researchers manually and systematically screened the article titles and abstracts and confirmed that the selected articles: (1) did not have as their participants robots, animals (e.g., monkeys), infants, or special populations (e.g., people with autism) because the main focus of this review is to examine the general trends of the eye tracking method applied in the schooling context; (2) used eye tracking devices, and (3) provided empirical evidence or evaluation. During the screening process, any inconsistent decisions among the four researchers were discussed and resolved. Finally, 81 papers were identified as the research sample pool of this review. Noticeably, there were papers involving more than one experiment. To include all the eye movement investigations, each of the experiments was counted as an independent study. As a result, 113 studies in total were identified.

4.2. Coding procedure

The content analysis consisted of three stages. In the first stage, the content of a selected paper was preliminarily coded based on its learning topics to specify different aspects of cognitive development. As mentioned in the literature review section, learning manifests itself in not only the acquisition of new information, but also in the development of perception, social cognition, language, mathematical thinking, causal/scientific reasoning, problem solving skills/strategies, and conceptual knowledge (Anderson, 2009; Goswami, 2008). As such, these major aspects of cognitive development were adopted to represent the categories of learning topics to be coded in the first coding stage. To be able to determine the learning topics studied in each selected paper, we looked for major research subjects related to each aspect of cognitive development from several well-recognized cognitive psychology textbooks (e.g. Anderson, 2009; Gagné, Yekovich, & Yekovich, 1993; Goswami, 2008). These research subjects for each aspect of cognitive development were then included as the subtopics for each learning topic discussed in the study. Thus, a coding scheme for analyzing the learning topics included in each selected paper was developed as shown in Table 3. Noticeably, to fulfill the study purpose, the learning topics listed in the coding scheme include subtopics related most to learning in the schooling context.

In the second stage, all papers of different learning topics were then coded for the research questions or tasks, eye movement measures and indications drawn from these eye movement measures. In the last stage, through cross-examination of the research questions/tasks and the eye movement indications identified in each paper, several thematic linkages were generated, which describe how the eye movement studies were connected to the issues of learning. The thematic linkages were

Table 3
The learning topics and their associated subtopics for content analysis.

| Learning topic	Associated subtopics
Perception	Object/visual recognition, spatial relations, animated relations (continuous actions)
Social cognition	Awareness of self and others, recognizing intentional actions by others, social referencing
Meaning-based representation	Concepts of basic or natural objects, schema (true categories and episodic memories)
Language	Phonological, lexical, grammatical, reading
Reasoning	Causes and effects, causal principles, coordination of theory and evidence, hypothesis testing, integration of information, metacognitive reasoning
Conceptual development	Basic-level/superordinate/subordinate categories or concepts (related to school subjects), conceptual change, domain-specific knowledge
Skill/strategy learning	Domain-general skills, domain-specific strategies
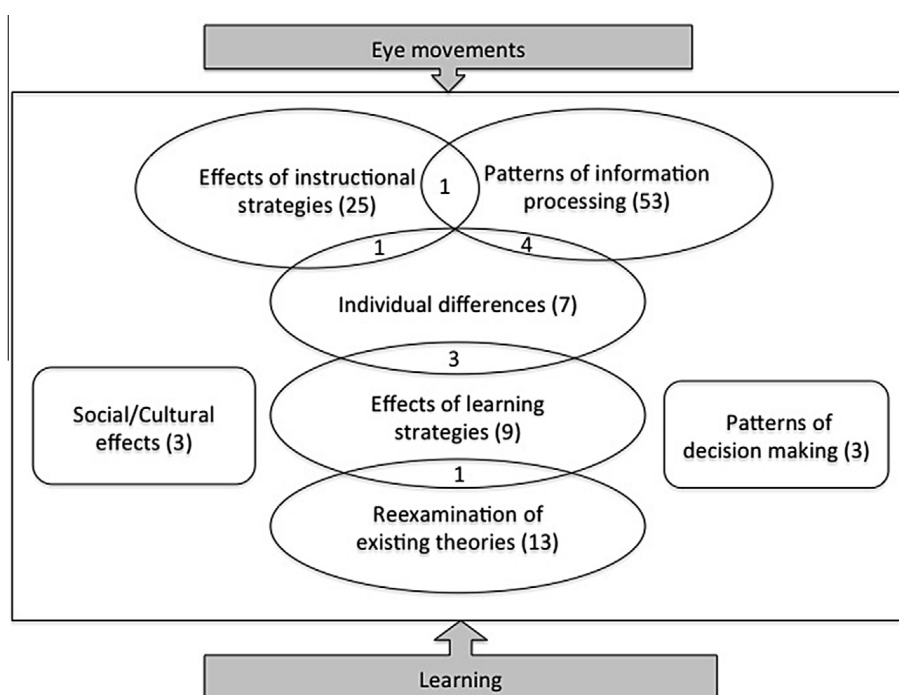
Fig. 1. Bridging framework between eye movements and learning.

defined as "learning themes." In brief, the researchers examined the research purposes and questions of a study from the text and then proceeded to identify what information the eye movement data could indicate for the research purposes and questions. For example, the main research task in the work of D'Melloa, Olney, Williams, and Hays (2012) was to evaluate the efficacy of a gaze-reactive tutoring system in promoting learning, motivation and engagement. Eye movement measures investigated in the study included gaze position and probability distributions of gaze events. The study found that students' attention indicated by the gaze patterns was affected by the tutoring system. Based on the abovementioned information, the learning theme of the study was classified as "the effects of instructional strategies." Three educational researchers with specialization in eye movement worked together to define and examine the learning themes.

A large table showing how the eye tracking technology has been used to reveal cognitive activities in relation to learning, abstracted from each reviewed paper, is listed in the Appendix. Finally, seven learning themes connecting the eye tracking method and learning were generated to form a bridging framework of eye movement research in education. The framework is displayed in Fig. 1. To solve the issue of coding reliability, three researchers collaboratively worked together on the coding procedure. Disagreements were solved after discussions among the researchers.

5. Results and discussion

5.1. Overall findings

By content analysis, it was found that the 81 papers (containing 113 studies) reviewed here discussed topics of learning such as perception, causal reasoning, social cognition, meaning-based representations, language, conceptual development,

and skills/strategy learning. Among these topics, conceptual development received the most attention (40 studies), followed by perception (25 studies) and language (23 studies). Only a few studies were dedicated to causal reasoning, social cognition, and skills/strategy learning (3, 5, and 6 studies, respectively). The initial analysis suggested that when the eye movement method was applied to studies related to learning, the focus of discussion was largely on the acquisition of new information or conceptual knowledge.

As far as eye movement measures are concerned, temporal measures were the most frequently employed overall (138 times, given that some studies used more than one measure), followed by frequency measures (55 times) and spatial measures (38 times). Rather than revealing basic cognitive mechanisms, eye movement measures, when applied to the studies related to learning, were used to disclose mostly the perceptual habits, mental efforts, and change or movement of attention on learning materials. In short, the eye movement data shown in the reviewed studies largely suggested real-time attention distribution. In due course, how exactly eye movement measures are related to the processes or outcomes of learning need to be further tested by studies incorporating adequate performance measurements. These measurements may include achievement tests, behavioral observations, log records, rate of accuracy, response time, introspective reflections and so forth.

5.2. The bridging framework

As mentioned previously, in the last stage of the coding procedure, the cross-examinations of the research questions and eye movement indications of each study across different learning topics eventually abstracted 7 learning themes out of the 113 reviewed studies. These themes include (1) Patterns of information processing, (2) Effects of instructional strategies, (3) Reexaminations of existing theories, (4) Individual differences, (5) Effects of learning strategies, (6) Social/Cultural effects, and (7) Decision making patterns. Noticeably, some of the papers embraced two themes in their design. Accordingly, a bridging framework was created as in Fig. 1, showing the 7 generative learning themes that specify how the eye tracking technology has been used to explore learning issues. In the following, an analysis of each learning theme is depicted.

5.2.1. Patterns of information processing

In our review, 53 studies were found to map the patterns of information processing. The majority of these works discussed the learning topics of language (18 studies), perception (19 studies), and meaning-based representations (9 studies). A few studies dealt with problems concerning conceptual development (4 studies), social cognition (2 studies), and psychomotor learning (1 study).

The patterns of information processing investigated in these studies include how learners acquire new words or recognize learned words (Arnold, Eisenband, Brown-Schmidt, & Trueswell, 2000; Bolger & Zapata, 2011; Brandt-Kobele & Höhle, 2010; Brown-Schmidt, 2009; Brusnighan & Folk, 2012; Chaffin, Morris, & and & Seely, 2001; Grüter, Lew-Williams, & Fernald, 2012; Schmiedtova, 2011; Shatzman & McQueen, 2006; Wonnacott, Newport, & Tanenhaus, 2008), how learners control and distribute their attention during visual searching, and how contextual, semantic or memory factors may affect object/visual recognition and the processes of visual searching (Beesley & Le Pelley, 2010; Brockmole & Le-Hoa Võ, 2010; Castelhano & Heaven, 2011; Goujon, Brockmole, & Ehinger, 2012; Guérard, Saint-Aubin, Boucher, & Tremblay, 2011; Karacan, Cagiltay, & Tekman, 2010; Koenig & Lachnit, 2011; Mou, Liu, & McNamara, 2009; Roderer, Krebs, Schmid, & Roebers, 2012; Tremblay, 2011; van Asselen, Sampaio, Pina, & Castelo-Branco, 2011; Wang & Mitchell, 2011; Welham & Wills, 2011). At a more basic level of learning, how humans learn object-based categories and face recognition has been discussed (Blair, Watson, & Meier, 2009; Goldinger, He, & Papesh, 2009; Henderson, Williams, & Falk, 2005; Hsiao & Cottrell, 2008; Huestegge & Koch, 2012; Liu & Chuang, 2011; Sekiguchi, 2011). As far as the higher level of learning is concerned, attention distributions during concept learning and problem solving have also been study targets (Bartolotti & Marian, 2012; Liu, Lai, & Chuang, 2011; Schneider, Maruyama, Dehaene, & Sigman, 2012). In addition, the few studies investigating social cognition and psychomotor learning reveal how learners learn to respond associatively to sensory (social) cues and how skills are obtained over time (Herwig & Horstmann, 2011; Mu, 2010). In short, due to the process characteristic, eye tracking technology has been extensively used to depict the patterns of information processing on various levels of learning.

5.2.2. Effects of instructional strategies

As for the 26 studies focusing on the effects of instructional strategies, nearly all of these studies involved conceptual development (22 studies), while only a few involved psychomotor learning (3 studies) or language learning (1 study). Most of the studies concerned how to design multimedia for better learning support. Specifically, various cues, guidance, displays, controls and presentations were manipulated and examined for the use of multimedia, especially animations, in related studies (Boucheix & Lowe, 2010; de Koning, Tabbers, Rikers, & Paas, 2010; Johnson & Mayer, 2012; Meyer, Rasch, & Schnotz, 2010; Ozcelik, Arslan-Ari, & Cagiltay, 2010; Ozcelik, Karakus, Kursun, & Cagiltay, 2009; Schmidt-Weigand, Kohnert, & Glowalla, 2010; Stieff, Hegarty, & Deslongchamps, 2011). Many studies focused on designs for text and graphic comprehension or problem solving (e.g., Ariasi & Mason, 2011; Blythe et al., 2012; Hegarty, Canham, & Fabrikant, 2010; Lewis & Mensink, 2012; Liu & Shen, 2011; She & Chen, 2009). Several studies attempted to examine the use of various mind tools, such as concept maps (Amadieu, van Gog, Paas, Tricot, & and & Marine, 2009), video annotation systems (Mu, 2010), simulated touch function (Wiebe, Minogue, Jones, Cowley, & Krebs, 2009), focused attention training (Pradhan et al., 2011), and gaze-based tutoring systems (D'Melloa, Olney, Williams, and Hays, 2012). In sum, these studies used eye-tracking techniques to examine

student learning states while interacting with multimedia learning environments. The results of these studies can provide valuable feedback for individualized learning system designs.

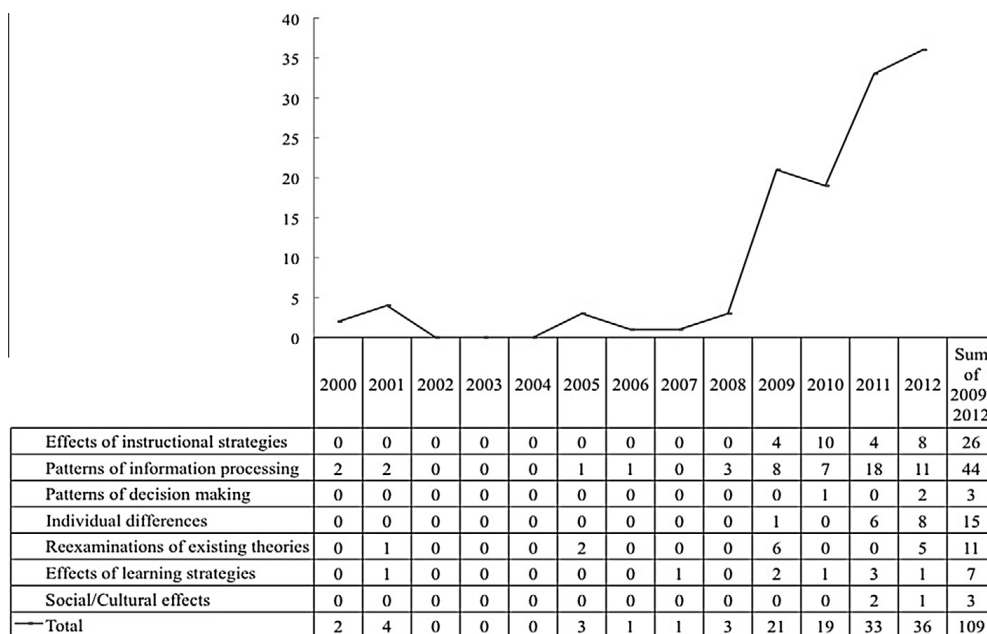### 5.2.3. Reexaminations of existing theories

Among the reviewed papers, we found that 14 studies aimed to reexamine the existing theories. Most of these studies were centered on the topics of conceptual development (7 studies) and perception (4 studies), while three studies were on the topics of meaning-based representation (1 study), language (1 study), and psychomotor learning (1 study). The theories under reexamination mainly included category learning (Blair, Watson, Walshe, & Maj, 2009; Rehder, Colner, & Hoffman, 2009; Rehder & Hoffman, 2005a,b), processes of visual search in learning (Hout & Goldinger, 2011; Jones & Kaschak, 2011), language learning (Whitford & Titone, 2012), and skill learning in complex tasks (Lee & Anderson, 2001). These theories seem to reflect mostly the basic levels of learning.

5.2.4. Individual differences

A total of 15 studies were found to focus on examining individual differences among learners. Most of them involved conceptual development (6 studies) and language learning (6 studies). Others dealt with psychomotor learning (2 studies), patterns of decision making (2 studies) and meaning-based representation (1 study). It is noticed that the majority of these studies concerned higher-level cognition, such as conceptual development and language learning, comparing learners with different characteristics. These characteristics included prior language background (Bartolotti & Marian, 2012; Grüter et al., 2012; Tremblay, 2011), prior domain knowledge (Balslev et al., 2012; Kim & Rehder, 2011; Ooms, De Maeyer, Fack, Van Assche, & Witlox, 2012; Tsai et al., 2012), domain expertise (Balslev et al., 2012), prior experience (Sekiguchi, 2011) and age level (Blythe et al., 2012; Isaacowitz & Choi, 2012; Neider & Kramer, 2011). Those investigations which focused on background knowledge or experience showed that the researchers are rooted in constructivist perspectives of learning, while those focused on age level showed that some studies examined learning from the developmental perspectives of learning.

5.2.5. Effects of learning strategies

Nine studies in this review used eye tracking technology to examine students' learning strategies and the effects of these strategies. The learning topics in this category ranged from conceptual development (3 studies), psychomotor learning (3 studies), and perception (2 studies) to meaning-based representation (1 study). A diversity of discussions were covered in this theme, including, for example, how learners process text, graphic and spatial information (Guérard, Tremblay, & Saint-Aubin, 2009; Smerecnik et al., 2010), how students attend to and select information during web searching (Miwa et al., 2011; Neider & Kramer, 2011), and how learners solve problems during complex tasks such as domain-specific multiple-choice tests (Tsai et al., 2012), multipart skill learning tasks (Lee & Anderson, 2001), and error judgment tasks (Wills, Lavric, Croft, & Hodgson, 2007). In short, studies in this theme emphasize the sequences of cognitive actions appearing in various learning and problem solving tasks.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Sum of 2009-2012
Effects of instructional strategies	0	0	0	0	0	0	0	0	0	4	10	4	8	26
Patterns of information processing	2	2	0	0	0	1	1	0	3	8	7	18	11	44
Patterns of decision making	0	0	0	0	0	0	0	0	0	0	1	0	2	3
Individual differences	0	0	0	0	0	0	0	0	0	1	0	6	8	15
Reexaminations of existing theories	0	1	0	0	0	2	0	0	0	6	0	0	5	11
Effects of learning strategies	0	1	0	0	0	0	0	1	0	2	1	3	1	7
Social/Cultural effects	0	0	0	0	0	0	0	0	0	0	0	2	1	3
Total	2	4	0	0	0	3	1	1	3	21	19	33	36	109

(Note: Ten studies discuss two learning themes, so the total number is 123 (113 + 10))

Fig. 2. Number of studies with respect to each learning theme from 2000 to 2012.

Table 4
Use of the eye movement measures related to different learning themes.

Learning theme	Temporal	Spatial	Count
Patterns of information processing	47	22	24
Effects of instructional strategies	47	7	15
Reexaminations of existing theories	17	1	5
Effects of learning strategies	12	3	2
Individual differences	9	1	7
Patterns of decision making	3	3	1
Social cultural effects	3	1	1
Total	138	38	55

5.2.6. Patterns of decision making

There were 3 studies discussing the patterns of decision-making in the scope of causal reasoning. Among them, one explored how people retrieved memories during decision making (Renkewitz & Jahn, 2012) and the other two discussed how people of different ages and knowledge backgrounds make choices when given task relevant information or how they monitor their memory during a choice task (Miller & Cassady, 2012; Roderer & Roebers, 2010). In sum, studies on the theme of patterns of decision making often took into consideration cognitive and developmental constraints.

5.2.7. Social cultural effects

There were 3 studies discussing social cultural effects. Two of these studies discussed the cultural differences in processing faces of difference races (Kelly et al., 2011; Nakabayashi et al., 2012) and the other discussed the relation between attention and social cognition (Kim & Mundy, 2012). Obviously, the exploration of the social-cultural effect is rare in eye movement studies related to learning.

It is worth mentioning that among the reviewed studies, we found 12 which involved more than one learning theme and, interestingly, the theme of individual differences was most often investigated with other learning themes, particularly the patterns of information processing, and the effects of learning strategies.

5.3. The research trend of the eye tracking method applied in learning-related studies

As Fig. 2 shows, the number of eye movement studies related to learning has increased significantly since 2009. With respect to the 7 learning themes, over 40% of these studies focused on describing patterns of information processing. Meanwhile, studies discussing the effects of instructional strategies have also grown significantly in the recent 3 years. Other than the abovementioned two themes, an increasing number of researchers are taking notice of individual differences. It seems that social/cultural effects and decision-making patterns are two themes that have just caught educational researchers' attention. Noticeably, these two themes are greatly studied in psychological research but without an educational focus. The developmental trend of the research over a decade suggests that educational researchers may have just started to notice the wide extent to which the eye-tracking method can be applied in the study of learning issues. Our framework also points out that other than the extensive discussions on information processing and instructional strategies, there are many other learning themes that can be explored using eye tracking methods, but which still lack substantive investigations. Since eye-tracking technology is dominantly used in the domain of psychology, there should be a clear push for educational researchers to make good use of this existing eye movement research. More conversations or interactions between psychologists and educational researchers are needed to help extend the scope of the new research application in education.

5.4. The use of eye movement measures in learning-related studies

After analyzing the eye movement measures used in the reviewed studies, *temporal* measures were found to be used most widely for all the learning themes, followed by *count* measures, except for the themes of *learning strategies* and *decision making patterns*. Table 4 shows the statistical results. This may be due to the fact that temporal and count data were easy to collect with the software available and were often used quantitatively. The spatial measures were the least used in the studies, which may be because the spatial indicators (e.g., fixation location and scan path) are typically analyzed in a qualitative way, which is more time and energy consuming. However, spatial measures were used more often than count measures for the themes of *learning strategies* and *decision making patterns.* This is reasonable because these two themes involve meta-cognitive skills, and to show meta-cognitive skills may require more sophisticated observations or analyses of fixation locations and sequences for a better conclusion. Moreover, the choice of eye-tracking measures is often motivated by specific research questions. Different research fields may focus on different types of measures. For example, in the field of reading comprehension the focus is mostly on temporal measures, while in the field of scene perception the focus is more often on spatial measures. Since the majority of the studies in the pool of this review were related to reading-oriented learning activities, it is

reasonable to obtain this result. In summary, it is important to have clear research questions or hypotheses in order to choose proper eye-tracking measures for examinations.

6. Conclusion

As our study results show, in these eye-tracking studies, the theme of information processing has received the most attention, followed by the effect of instructional strategies. Meanwhile, the number of studies aiming to examine the existing theories as well as probing individual differences has grown significantly in recent years. Nevertheless, fewer studies have been devoted to analyzing the effects of learning strategies, patterns of decision-making and social/cultural factors. In short, the foci of discussions presented in the reviewed studies seem to revolve around the acquisition of new information. As far as eye movement measures are concerned, the temporal forms provide the major information about the learning processes, although the choice of measures is often motivated by the specific research question. Our review also indicates that the use of eye tracking methods in studying learning-related issues has proliferated in the recent 3 years. Such a result suggests that the eye tracking method provides a promising channel for educational researchers to connect learning outcomes to relevant cognitive processes.

7. Future studies

As the framework indicates, eye-tracking technology is able to reveal various learning themes that describe underlying psychological processes of different learning objectives. However, the unbalanced numbers of studies found across the seven learning themes suggest that more efforts are needed to explore learning topics such as reasoning, skill learning and the effects of social cognition.

Based on our analysis, it is clear that the studies included in our review have successfully employed eye-tracking measures to examine or explore the cognitive processes in various topics within various themes. Temporal indicators were the most frequently used measures across all learning topics and themes. Count and spatial indicators were used depending on the research questions, for example, number of fixations was often used to show attention distribution, while scan paths were used to imply metacognitive strategies. Future studies can continue to explore the correlations between various eye-tracking measures and various learning performance measures. Understanding the above relationships should be the first step in applying eye-tracking techniques for further educational studies. Therefore, more studies are needed to build up a connection between the micro-measures (i.e., eye-tracking measures) and the macro-measures (i.e., performance or behavioral measures).

As Fig. 2 (year-theme histogram) shows, researchers started to extensively examine individual differences in 2011. It appears that patterns of eye movements are good measures to reveal people's (such as experts vs. novices) distinct cognitive processes. Accordingly, educators can make use of the information about individual differences to develop proper adaptive learning systems that take into consideration learner characteristics. There are studies employing eye movement data of skilled persons to guide others' attention, but the application is limited to the learning of basic cognitive skills or clinical practice (e.g., Litchfield, Ball, Donovan, Manning, & Crawford, 2010; van Gog, Jarodzka, Scheiter, Gerjets, & Paas 2009). Furthermore, adaptive learning systems with eye-tracking-embedded technology may also be developed in the future to provide dynamic scaffoldings for all students for better learning in all learning domains. For example, interactive learning systems embedded with eye-tracking equipment may dynamically diagnose students' learning states and needs as well as providing instant help or adapted scaffolding materials according to the eye movement data tracked by the systems.

In addition, data mining techniques such as sequential analyses may be incorporated as an approach for analyzing the huge amount of eye-tracking data. Moreover, visualizations of eye fixation data such as heat maps or hot zone pictures are powerful for demonstrating allocations of visual attention as a whole picture for individual persons or specific groups of people. Understanding how to make use of the techniques or software is important for educational researchers who are interested in conducting eye-tracking studies. On the other hand, interdisciplinary collaboration across computer engineering, visual studies and educational technology is encouraged in the future for developing more user-friendly and useful tools for educational research.

Furthermore, all the eye tracking studies included in the study used only ONE eye tracker in the lab environment, which somewhat restricts the practical use of the equipment in studying interactions between different subjects, and also minimizes the generalization of the results for authentic learning. For future studies, researchers could employ two or more eye trackers to investigate social cognition issues (e.g., parent–child interactions during storybook reading) or students' moment-to-moment eye fixations in realistic classroom settings (e.g., what and where students are looking during teachers' presentations).

However, considering the high price of eye trackers, which means that they are not easily accessible for educators, we call for the development of lower priced devices that are designed specifically for educational purposes. Such devices do not need to have a very high sampling rate or complicated data analysis programs, which are usually the reasons for the high cost of eye tracking systems. For most educators, sentences, passages or graphical forms of information are the central regions of interest. In addition, in order to be used in authentic learning environments, eye trackers should allow slight head movements or even full mobility. Considering these needs, a high sampling rate is by no means the absolute criterion for

choosing an eye tracking system for use in educational settings. Besides, as far as the data analysis software is concerned, collaboration between software engineers and educational researchers could help to modulate existing data analysis programs, making them suitable for education studies while reducing the cost of software development. In short, it is possible to cut down the price of eye tracking systems if we take into consideration the specific needs and features of educational research.

In fact, there are up-and-coming open source eye-trackers that are already available at a fraction of the price of the usual proprietary suppliers. For example, the open-source ITU Gazetracker developed by San Agustin and associates (2010) is a promising software that can transform web cameras or digital video recorders into eye trackers. Meanwhile, a new wave of computer engineering research is starting the technological revolution of pervasive eye-tracking technology integrated into smart phones, tablets, laptops, etc. It is highly likely that such technological developments will promote eye trackers as easily accessible devices that can be utilized widely in educational contexts. However, without input from educators, these developing technologies could not fulfill the needs of the educational field. Hence, collaboration is required between developers of such technologies and educational researchers.

Finally, we call for attention to the relevant theoretical issues in future studies. In this review, a bridging framework is proposed to show how eye-tracking methods have been applied to educational studies and what studies should be conducted to gain more understandings of student learning. One issue that we have not analyzed here concerns the theories underpinning all of these studies. Although not every study explicitly discusses its underlying principles, it is clear that many of the studies reviewed in the paper are based on constructivist and developmental perspectives of learning (e.g., Amadieu et al., 2009; Blair, Watson, & Meier, 2009; Blair, Watson, Walshe et al., 2009; Kim & Mundy, 2012; Neider & Kramer, 2011), Nevertheless, what exactly the normative learning theories are to guide eye movement studies, what prescriptive theories (e.g., multimedia learning theory, cognitive load theory, etc.) that these studies actually used in their experimental designs, and whether the research findings support the theories are not analyzed in this study. In addition, as suggested previously, since interdisciplinary and collaborative studies are needed in the future, whether there is a coherent theoretical framework that can guide all such research should be explored. Analyses of the theoretical issues will help educational researchers to appropriately apply the eye tracking methods in their studies. It is hoped that such a review of the theoretical bases will appear in the near future.

Acknowledgement

Appendix. Analysis of connection to learning in each reviewed study

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
1	Amadieu et al. (2009)	This study explored the effects of prior knowledge (high vs. low; HPK and LPK) and concept-map structure (hierarchical vs. network; HS and NS) on disorientation, cognitive load, and learning from non-linear documents on "the infection process of a retrograde virus (HIV)"	Conceptual development	Total fixation duration, number of fixations, proportion of fixations saccades	Test	Effects of instructional strategies Individual differences
2	Ariasi and Mason (2011)	This study examined whether reading a refutational or non-refutational text would induce different cognitive processing, as revealed by eye-movement analyses	Conceptual development	First pass duration, total fixation duration, second pass fixation, total reading time	Pretest and posttest, knowledge test	Effects of instructional strategies

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
3	Arnold et al. (2000)	This study investigated how listeners use gender and accessibility in on-line pronoun comprehension	Language	Proportion	Accuracy	Patterns of information processing
4	van Asselen et al. (2011)	This study aimed to study how object information can facilitate a visual search during an object-based contextual cueing task	Perception	Number of fixations, average number of fixations, fixation duration, total number of saccades, saccade amplitude	Response time(RT)	Patterns of information processing
5	Balslev et al. (2012)	This study investigated visual attention and associated clinical reasoning processes	Conceptual development	Percentage of reading time	Diagnostic accuracy, think aloud reasoning, time on task	Individual differences
6	Bartolotti and Marian (2012)	This study investigated the effect of bilingualism on the ability to control native-language interference	Language	Proportion of fixations	Accuracy, RT	Individual differences
7	Beesley and Le Pelley (2010)	This study examined the impact of blocking on overt attention during a human contingency learning task	Perception	Location of gaze	Accuracy, RT	Patterns of information processing
8	Blair, Watson, and Meier (2009)	This study investigated an assumption imbedded in formal models of categorization: error is necessary for attentional learning	Meaning-based representations	Total fixation duration, fixation position	N/A	Patterns of information processing
9	Blair, Watson, Walshe, and Maj (2009)	This study investigated the flexibility of learned attention	Conceptual development	Total fixation duration, number of fixations, average fixation duration, proportion, gaze	Accuracy	Reexaminations of existing theories
10	Blythe et al. (2012)	This study examined whether inserting spaces between words in Chinese text would help children learn to read new vocabulary	Language	First fixation duration, gaze duration, total fixation duration, refixation probability, number of regressions	Accuracy	Effects of instructional strategies
11	Blythe et al. (2012)	This study examined whether inserting spaces between words in Chinese text would help children learn to read new vocabulary	Language	First fixation duration, gaze duration, total fixation duration, refixation probability,	Accuracy	Individual differences

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
12	Bolger and Zapata (2011)	This study tested whether and how semantic relatedness inhibits learning given more contexts	Language	Fixation duration, gaze, total gaze duration, first-pass gaze duration, number of gazes	Accuracy, RT	Patterns of information processing
13	Boucheix and Lowe (2010)	This study used eye tracking to investigate a novel cueing approach for directing learner attention to low salience, high relevance aspects of a complex animation	Conceptual development	Total fixation duration, number of fixations, proportion, total reading time	Test	Effects of instructional strategies
14	Brandt-Kobele and Höhle (2010)	This study investigated whether German 3- to 4-year-olds take advantage of the information provided by verb inflection in sentence comprehension	Language	Fixation duration	Accuracy, RT	Patterns of information processing
15	Brockmole and Le-Hoa Võ (2010)	This study investigated how memory for relational contingencies that emerge across different scenes can be exploited to guide attention	Perception	Number of fixations, location of fixations, location of gaze	Accuracy, RT	Patterns of information processing
16	Brown-Schmidt (2009)	This study presented the results of three experiments that re-examine the question of whether partner-specific information is used by early, on-line interpretation processes	Language	Time to first fixation, total fixation number	N/A	Patterns of information processing
17	Brusnighan and Folk (2012)	This study investigated how skilled readers use contextual and morphemic information in the process of incidental vocabulary acquisition during reading	Language	Average fixation duration, first fixation duration, go-past time, regression, second-pass time	Vocabulary test (accuracy, choice time, sentence reading time)	Patterns of information processing
18	Castelhano and Heaven (2011)	This study investigated the influence of scene gist, learned spatial associations and how these sources of information relate	Perception	Latency to target, number of fixations, first fixation duration, first gaze duration	Accuracy, RT	Patterns of information processing

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
19	Chaffin et al. (2001)	This study examined how readers established the meaning of a new word from the sentence context during silent reading	Language	Total fixation duration, gaze duration, total reading time, number of regressions	Test	Patterns of information processing
20	de Koning et al. (2010)	This study examined how visual attentional resources are allocated when learning from a complex animation	Conceptual development	Number of fixations, average fixation duration, proportion	Comprehension test, transfer test, mental effort question, verbal protocol	Effects of instructional strategies
21	D'Melloa et al. (2012)	This study evaluated the efficacy of the gaze-reactive tutor in promoting learning, motivation and engagement	Conceptual development	Gaze position, probability of gaze events	Knowledge test, engagement measures, subjective impressions measures, individual difference measures	Effects of instructional strategies
22	Goldinger et al. (2009)	The goal was to replicate the standard ORB, contrasting recognition memory to Asian and Caucasian faces, as a function of study time	Meaning-based representation	Total fixation duration, average fixation duration, number of fixations, proportion, saccade	Test, accuracy	Patterns of information processing
23	Goujon et al. (2012)	This study examined the role of color features (cuing effect), and determining the nature of learning mechanisms	Perception	Time to first fixation	RT, explicit memory tasks, distance between true and recalled places across different conditions	Patterns of information processing
24	Grüter et al. (2012)	This study tested whether gender-marking on the determiner facilitates interpretation of the following noun	Language	Proportion of reading time	Language proficiency measures, RT	Patterns of information processing individual differences
25	Guérard et al. (2011)	This study examined the role of awareness in anticipation and recall performance, using the Hebb repetition paradigm	Perception	Gaze duration (total fixation duration)	Recall performance	Patterns of information processing
26	Guérard et al. (2009)	This study examined the effect of ocular suppression on spatial serial recall and the path length effect	Perception	Total fixation duration	Accuracy	Effects of learning strategies

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
27	Hegarty et al. (2010)	This study examined how bottom-up and top-down processes interact when people view and make inferences from complex visual displays (weather maps)	Conceptual development	Total fixation duration, number of fixations, locations of fixations	Test, RT	Effects of instructional strategies
28	Henderson et al. (2005)	This study investigated (1) do eye movements facilitate face learning? (2) are the eye-movement patterns generated during face learning recapitulated during recognition? and (3) do eye movements change during face learning and recognition?	Meaning-based representations	Total fixation duration, number of fixations, fixation location, proportion, gaze, saccades	Accuracy, RT	Patterns of information processing
29	Herwig and Horstmann (2011)	This study diagnosed whether participants acquire bidirectional associations between their actions and their actions' effects: (1) whether saccades and their effects become associated; (2) whether these saccade-effect associations are used to select a saccade	Social Cognition	Number of saccades, fixation location	RT	Patterns of information processing
30	Hoffman and Rehder (2010)	This study tested the hypothesis that classification training produces less flexible category representations	Conceptual development	Average fixation duration, proportion, average saccade length	Speed	Effects of instructional strategies
31	Hout and Goldinger (2011)	This study investigated under what conditions during visual search does the incidental learning of BK occur? and what does viewing behavior reveal about the efficiency of attentional deployments over time?	Perception	Number of fixations, average fixation durations, total fixation duration	Token discrimination test (memory test), search RT, recognition accuracy	Reexaminations of existing theories
32	Hsiao and Cottrell (2008)	This study examined the influence of the number of fixations on face recognition performance with participants' natural eye movements	Meaning-based representation	Total fixation duration, number of fixations, fixation location, scan path	N/A	Patterns of information processing

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
33	Huestegge and Koch (2012)	This study investigated what eye movements can tell about the mechanisms of transferring relevant stimuli into memory	Meaning-based representations	EXP I: number of fixations, refixation probability, gaze position, fixation duration, saccade length EXP II: number of fixations, average fixation duration, saccade length	Accuracy	Patterns of information processing
34	Isaacowitz and Choi (2012)	This study investigated how age-related changes in attention to negative but relevant information about skin cancer risk reduction influenced both subsequent health behavior and mood regulation	Conceptual development	Percentage of fixations	Self report mood rating, behavior outcome measures	Individual differences
35	Jarodzka et al. (2012)	This study applied a novel instructional method to teach these skills by showing the learners how an expert model visually searches for and interprets symptoms	Conceptual development	Gaze positions, total time not fixated, total reading time	Multiple-choice questions	Effects of instructional strategies
36	Johnson and Mayer (2012)	This study examined how spatial contiguity affects cognitive processing learning, and whether learners who receive an integrated presentation perform better on transfer tests than those who received a separated presentation	Conceptual development	Scanpaths, proportion of transition, proportion of fixation, total fixation duration	Spatial ability tests	Effects of instructional strategies
37	Jones and Kaschak (2011)	This study examined statistical learning in visual searching	Perception	Saccade latencies, saccade locations, number of saccades	RT, accuracy	Reexaminations of existing theories
38	Karacan et al. (2010)	This study examined whether the effect of scene familiarity could be generalized to natural environments. Does familiarity with scene content improve detection of scene changes in a 3D virtual reality environment?	Perception	Total fixation duration, fixation position, time to first fixation	Verbal report	Patterns of information processing

Appendix. Analysis of connection to learning in each reviewed study (continued)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
39	Kelly et al. (2011)	This study explored the origins of cultural differences in eye movements when encoding and recognizing human faces and potential cultural divergence in general face processing strategies	Social cognition	Fixation distribution	Accuracy, RT	Social/cultural effects
40	Kim and Mundy (2012)	This study measured two types of JA in adults, Initiating Joint Attention (IJA) and Responding to Joint Attention	Social cognition	Total reading time	Memory test (standardized spatial working memory task)	Social/cultural effects
41	Kim and Rehder (2011)	This study used eye tracking during knowledge-based category learning to determine (1) whether knowledge does indeed have any effect on selective attention; (2) whether any effect of knowledge on attention is limited to which sources of information learners initially consider or whether it can emerge as a result of experience with category members; (3) whether error feedback is required to mediate those shifts	Conceptual development	Number of fixations, proportion fixation, proportion fixation duration	Accuracy, RT	Individual differences
42	Koenig and Lachnit (2011)	This study assessed the effect of memory interference on saccadic curvature	Perception	Saccade	N/A	Patterns of information processing
43	Lee and Anderson(2001)	This study monitored the eye movements of people performing the KAATC task to see whether the learning in this task could also be explained by the attentional learning hypothesis	Psychomotor learning	Total fixation duration	N/A	Effects of learning strategies Reexaminations of existing theories
44	Lewis and Mensink (2012)	This study investigated whether readers direct additional attention to and learn more from sentences that are potentially relevant to a set of pre-reading questions	Conceptual development	First-pass progressive fixations, first-pass reinspections lookbacks	N/A	Effects of instructional strategies

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
45	Liu and Chuang(2011)	This study explored learners' information processing patterns when the information is encoded in different formats and uncovered how different forms of presentations affect learners' processing of information in multimedia learning environments	Meaning-based representation	Number of fixations, fixation duration, location of fixations, number of saccades, total number of saccades, saccade length	RT	Patterns of information processing
46	Liu and Shen (2011)	This study investigated students' learning process of the concept of concentration at the elementary school level in Taiwan	Conceptual development	Scanpath, total fixation duration, average fixation duration, total saccade duration, total blink duration, total reading time, average saccade duration, average blink duration	Interview	Effects of instructional strategies
47	Liu et al. (2011)	This study aimed to determine the impact of redundant onscreen text information on viewers' cognitive processes with respect to multimedia information	Conceptual development	Number of fixations, fixation duration, average fixation duration	N/A	Patterns of information processing
48	Meyer et al. (2010)	This study tested whether the presentation speed affects differences in visual attention	Conceptual development	Total fixation duration, proportion, total gaze duration	Test	Effects of instructional strategies
49	Miller and Cassady (2012)	This study examined strategies associated with deciding which of two NFPs, presented side-by-side, was healthier	Casual Reasoning	Frequency of saccades, scanpath	Knowledge test, motivation test	Decision making patterns
50	Miwa et al. (2011)	This study reported a method for closely observing, eliciting and visualizing exploratory search processes with embedded information encountered in context	Conceptual development	Gaze point, gaze duration (total fixation duration)	Interview, questionnaire, think-aloud, link depth	Effects of learning strategies

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
51	Mou et al. (2009)	This study investigated whether the spatial reference directions that are used to specify objects' locations in memory can be solely determined by layout geometry.	Perception	Locations of fixations, scanpath	N/A	Patterns of information processing
52	Mu (2010)	This study explored users' video note-taking behaviors and examined the effect of the new Smartlink design	Psychomotor learning	Gaze (fixation position) scanpath	Reaction time, personal note, discussion transcript	Effects of instructional strategies Patterns of information processing
53	Nakabayashi et al. (2012)	This study examined the influences of verbalization on face learning or recognition processes	Social cognition	Number of fixations, fixation time, total reading time	N/A	Social/cultural effect
54	Neider and Kramer (2011)	This study investigated (1) Do older adults still possess the ability to use preexisting spatial associations inherent in the target object and search scene in order to augment their search performance, and if so, are the performance benefits similar to those shown by younger adults? (2) If older adults prove able to use contextual information, what is the time course of such usage?	Psychomotor learning	Number of fixations, total fixation duration, initial saccades, gaze location	Accuracy (error rate), RT	Effects of learning strategies Individual differences
55	Ooms et al. (2012)	This study aimed to obtain insight into users' cognitive processes while working with dynamic and interactive maps	Conceptual development	Mean fixation duration, mean fixation count, fixation distribution	RT	Individual differences
56	Ozcelik et al. (2009)	This study investigated the underlying cause of the color coding effect by utilizing eye movement data	Conceptual development	Average fixation duration, time to first fixations, total fixation duration	Test	Effects of instructional strategies
57	Ozcelik et al. (2010)	This study aimed to examine the effects of signaling on learning outcomes and to reveal the underlying reasons for this effect by using eye movement measures	Conceptual development	Total fixation duration, number of fixation, average fixation duration, time to first fixation, probability	Prior knowledge test, retention test, transfer test, (open-ended question) matching test	Effects of instructional strategies

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
58	Pradhan et al. (2011)	This study investigated whether a rather simple, one hour PC-based training program using error learning as a key component would reduce the number of especially long glances away from the forward roadway on the open road	Psychomotor learning	Number of fixations, fixation duration, number of gazes, gaze duration, gaze location	RT	Effects of instructional strategies
59	Rehder and Hoffman (2005a)	This study investigated whether participants would limit their attention to only those stimulus dimensions needed to classify each structure and whether the changes in eye movements during learning would support a gradual or rule-based learning account	Conceptual development	Proportion	N/A	Reexaminations of existing theories
60	Rehder et al. (2009)	This study distinguished between CCL (category-centered learning hypothesis) and the alternative category-to-feature rule hypothesis using an eye tracker	Conceptual development	Total fixation duration, average fixation duration, proportion, probability	N/A	Reexaminations of existing theories
61	Rehder and Hoffman (2005b)	This study tested D. L. Medin and M. M. Schaffer's (1978) 5–4 category structure (indicating the superiority of multiplicative prototype, MPM)	Meaning-based representations	Total fixation duration, number of fixations, average fixation duration, proportion	Accuracy	Reexaminations of existing theories
62	Renkewitz and Jahn (2012)	This study investigated memory-based decision making processes	Casual Reasoning	Scanpath, total fixation durations, proportion of total reading time	Decision patterns, decision time	Decision making patterns
63	Roderer and Roebers (2010)	This study investigated the effects of memory retrieval processes on monitoring judgments, item difficulty in a vocabulary learning task	Causal Reasoning	Fixation duration, gaze, gaze paths (gaze)	Accuracy, RT	Decision making patterns
64	Roderer et al. (2012)	This study explored selectivity in encoding, aspects of attentional control and their contribution to learning performance	Perception	average fixation duration	Recognition of target items, accuracy, RT	Patterns of information processing

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
65	Schneider et al. (2012)	This study investigated whether an expression has to be scanned sequentially while the nested syntactic structure is being computed or whether this structure can be extracted quickly and in parallel	Conceptual development	Number of fixations scanpath	Accuracy, RT	Patterns of information processing
66	Schmidt-Weigand et al. (2010)	This study examined the effect of instruction pace on viewing behavior, that is, the way learners split their visual attention between written text and visualizations, as well as how text modality affects this viewing behavior in system-paced instruction	Conceptual development	Total fixation duration, saccades, inter-scanning number	Prior experience, retention test, transfer test, visual memory test	Effects of instructional strategies
67	Schmidt-Weigand, Kohnert, and Glowalla (2010)	This study examined how learners split their visual attention between written text and visualization when they control the pace of instruction and how the learners' viewing behavior in self-paced instruction is affected by text modality	Conceptual development	Total fixation duration, number of fixations, total reading time	Test, prior experience, retention test, transfer test, (open-ended question) visual memory test	Patterns of information processing
68	Schmiedtova (2011)	This study examined (1) what methods can be employed when studying the 'cognitive profile' of near-native L2 speakers, (2) what L2 population should be in focus, and (3) what psycholinguistic processes should be discussed	Language	Number of fixations, total gaze	RT	Patterns of information processing
69	Sekiguchi (2011)	This study examined the relationship between individual differences in face memory and eye fixation patterns on faces	Meaning-based representation	Number of fixations, total fixation duration, fixation distribution, number of gazes	Accuracy, RT	Individual differences Patterns of information processing
70	Shatzman and McQueen (2006)	This study examined the involvement of prosodic knowledge in the recognition of newly learned words	Language	Number of fixation, proportion, fixation position	Accuracy	Patterns of information processing

Appendix. Analysis of connection to learning in each reviewed study (*continued*)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
71	She and Chen (2009)	This study investigated the effects of presentation modes of multimedia learning material on students' mitosis and meiosis learning processes and performance	Conceptual development	Total reading time, fixation number, average fixation duration	Test	Effects of instructional strategies
72	Smerecnik et al. (2010)	This study aimed to examine two possible mechanisms (cognitive workload and attention) directed to the risk information	Conceptual Development	Number of fixation, fixation duration, percentage fixations	RT	Effects of Learning strategies
73	Stieff et al. (2011)	This study was to (1) evaluate students' ability to coordinate representations using multi-representational displays for teaching chemistry, and (2) examine the complementary contributions of eye fixation data and verbal protocols quantitatively	Conceptual development	Number of fixation, total fixation duration, saccades, gaze	Accuracy, RT	Effects of instructional strategies
74	Tremblay (2011)	This study investigated how native English speakers of different proficiencies in French and native French speakers from France parse vowel-initial words preceded by liaison/z/, and whether the procedure they adopt for segmenting real words also generalizes to nonce words	Language	Number of fixations, proportion of fixation	Accuracy, RT	Individual differences
75	Tsai et al. (2012)	This study examined students' visual attention when solving a multiple-choice science problem	Conceptual development	Fixation duration, average fixation duration, scanpath	Problem solving performance	Effects of learning strategies Individual differences
76	Wang and Mitchell (2011)	This study examined the role of attention in human perceptual learning	Perception	Gaze duration (total fixation duration)	Accuracy (mean proportion of correct responses)	Patterns of information processing
77	Welham and Wills (2011)	This study investigated three predictions of the McLaren and Mackintosh model	Perception	Total reading time	Accuracy, similarity rate	Patterns of information processing

Appendix. Analysis of connection to learning in each reviewed study (continued)

ID	Author	Research questions/ purposes	Related learning topic	Eye movement measures	Performance measures	Indication for learning (Learning theme)
78	Whitford and Titone (2012)	This study investigated whether the degree of current L2 exposure modulates the relative size of L1 and L2 frequency effects	Language	First fixation duration, gaze duration, skipping rate, proportion of regressions, total reading time	N/A	Reexaminations of existing theories
79	Wiebe et al. (2009)	This study looks at a simulation of the principles of levers using both visual and haptic feedback	Psychomotor learning	Total fixation duration, fixation number, average fixation duration	Test	Effects of instructional strategies
80	Wills et al. (2007)	This study employed electrophysiological measures to reveal early attentional differentiation of events that differ in their previous involvement in errors of predictive judgment	Meaning-based representations	Average fixation duration, proportion, total reading time	Accuracy	Effects of learning strategies
81	Wonnacott et al. (2008)	This study investigated whether participants could learn verb-specific construction constraints	Language	Proportion	Test	Patterns of information processing

References

Note: Papers marked with an asterisk (∗) are those selected for the current review

∗Amadieu, F., van Gog, T., Paas, F., Tricot, A., & Marine, C. (2009). Effects of prior knowledge and concept-map structure on disorientation, cognitive load, and learning. *Learning and Instruction, 19*, 376–386.

Anderson, J. (2009). *Cognitive psychology and its implication*. NY: Worth Publishers.

Anderson, C. W. (2007). Perspectives on science learning. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 3–30). NY: Routledge.

∗Ariasi, N., & Mason, L. (2011). Uncovering the effect of text structure in learning from a science text: An eye-tracking study. *Instructional Science, 39*, 581–601.

∗Arnold, J. E., Eisenband, J. G., Brown-Schmidt, S., & Trueswell, J. C. (2000). The rapid use of gender information: Evidence of the time course of pronoun resolution from eye tracking. *Cognition, 76*, B13–B26.

∗Balslev, T., Jarodzka, H., Holmqvist, K., de Grave, W., Muijtjens, A. M., Eika, B., van Merriënboer, J., & Scherpbier, A. J. (2012). Visual expertise in paediatric neurology. *European Paediatric Neurology Society, 16*, 161–166.

∗Bartolotti, J., & Marian, V. (2012). Language learning and control in monolinguals and bilinguals. *Cognitive Science, 36*, 1129–1147.

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin, 91*, 276–292.

∗Beesley, T., & Le Pelley, M. E. (2010). The influence of blocking on overt attention and associability in human learning. *Journal of Experimental Psychology: Animal Behavior Processes, 10*, 1–7.

∗Blair, M. R., Watson, M. R., & Meier, M. M. (2009). Errors, efficiency, and the interplay between attention and category learning. *Cognition, 112*, 330–336.

∗Blair, M. R., Watson, M. R., Walshe, R. C., & Maj, F. (2009). Extremely selective attention: Eye-tracking studies of the dynamic allocation of attention to stimulus features in categorization. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(5), 1196–1206.

∗Blythe, H. I., Liang, F., Zang, C., Wang, J., Yan, G., Bai, X., & Liversedge, S. P. (2012). Inserting spaces into Chinese text helps readers to learn new words: An eye movement study. *Journal of Memory and Language, 67*, 241–254.

∗Bolger, P., & Zapata, G. (2011). Semantic categories and context in L2 vocabulary learning. *Language Learning, 61*(2), 614–646.

∗Boucheix, J. M., & Lowe, R. (2010). An eye tracking comparison of external pointing cues and internal continuous cues in learning with complex animations. *Learning and Instruction, 20*, 123–135.

∗Brandt-Kobele, O.-C., & Höhle, B. (2010). What asymmetries within comprehension reveal about asymmetries between comprehension and production: The case of verb inflection in language acquisition. *Lingua, 120*, 1910–1925.

∗Brockmole, J. R., & Le-Hoa Võ, M. (2010). Semantic memory for contextual regularities within and across scene categories: Evidence from eye movements. *Attention, Perception, & Psychophysics, 72*(7), 1803–1813.

∗Brown-Schmidt, S. B. (2009). Partner-specific interpretation of maintained referential precedents during interactive dialog. *Journal of Memory and Language, 61*, 171–190.

∗Brusnighan, S. M., & Folk, J. R. (2012). Combining contextual and morphemic cues is beneficial during incidental vocabulary acquisition: Semantic transparency in novel compound word processing. *Reading Research Quarterly, 47*(2), 172–215.

∗Castelhano, M. S., & Heaven, C. (2011). Scene context influences without scene gist: Eye movements guided by spatial associations in visual search. *Psychonomic Bulletin & Review, 18*, 890–896.

∗Chaffin, R., Morris, R. K., & Seely, R. E. (2001). Learning new word meanings from context: A study of eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*(1), 225–235.

∗de Koning, B. B., Tabbers, H. K., Rikers, R., & Paas, F. (2010). Attention guidance in learning from a complex animation: Seeing is understanding? *Learning and Instruction, 20*, 111–122.

D'Melloa, S., Olney, A., Williams, C., & Hays, P. (2012). Gaze tutor: A gaze-reactive intelligent tutoring system. *International Journal of Human-Computer Studies, 70*, 377–398.

Duchowski, A. (2007). *Eye tracking methodology: Theory and practice*. London: Springer.

Gagné, E. D., Yekovich, C. W., & Yekovich, F. R. (1993). *The cognitive psychology of school learning*. NY: Longman.

Galván, A. (2010). Neural plasticity of development and learning. *Human Brain, Mapping, 31*, 879–890.

Gilman, E., & Underwood, G. (2003). Restricting the field of view to investigate the perceptual spans of pianists. *Visual Cognition, 2*, 201–232.

Ginsburg, H. P., & Opper, S. (1988). *Piaget's theory of intellectual development*. NJ: Printice Hall.

Goldberg, J. H., & Helfman, J. I. (2011). Eye tracking for visualization evaluation: reading values on linear versus radial graphs. *Information Visualization, 10*(3), 182–195.

Goldberg, H. J., & Kotval, X. P. (1999). Computer interface evaluation using eye movements: Methods and constructs. *International Journal of Industrial Ergonomics, 24*, 631–645.

∗Goldinger, S. D., He, Y., & Papesh, M. H. (2009). Deficits in cross-race face learning: Insights from eye movements and pupillometry. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(5), 1105–1122.

Goswami, U. (2008). *Cognitive development – The Learning Brain*. NY: Psychology Press.

∗Goujon, A., Brockmole, J. R., & Ehinger, K. A. (2012). How visual and semantic information influence learning in familiar contexts. *Journal of Experimental Psychology: Human Perception and Performance, 38*(5), 1315–1327.

∗Grüter, T., Lew-Williams, C., & Fernald, A. (2012). Grammatical gender in L2: A production or a real-time processing problem? *Second Language Research, 28*(2), 191–215.

∗Guérard, K., Saint-Aubin, J., Boucher, P., & Tremblay, S. (2011). The role of awareness in anticipation and recall performance in the hebb repetition paradigm: Implications for sequence learning. *Memory & Cognition, 39*, 1012–1022.

∗Guérard, K., Tremblay, S., & Saint-Aubin, J. (2009). The processing of spatial information in short-term memory: Insights from eye tracking the path length effect. *Acta Psychologica, 132*, 136–144.

∗Hegarty, M., Canham, M. S., & Fabrikant, S. I. (2010). Thinking about the weather: How display salience and knowledge affect performance in a graphic inference task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*(1), 37–53.

Hegarty, M., Mayer, R. E., & Green, C. (1992). Comprehension of arithmetic word problems: Evidence from students' eye fixations. *Journal of Educational Psychology, 84*(1), 76–84.

∗Henderson, J. M., Williams, C. C., & Falk, R. J. (2005). Eye movements are functional during face learning. *Memory & Cognition, 33*(1), 98–106.

∗Herwig, A., & Horstmann, G. (2011). Action–effect associations revealed by eye movements. *Psychonomic Bulletin & Review, 18*, 531–537.

Hess, E. H., & Polt, J. M. (1964). Pupil size in relation to mental activity during simple problem-solving. *Science, 143*(3611), 1190–1192.

∗Hoffman, A. B., & Rehder, B. (2010). The costs of supervised classification: The effect of learning task on conceptual flexibility. *Journal of Experimental Psychology: General, 139*(2), 319–340.

Holmqvist, K., Nystrom, M., Andersson, R., Dewhurst, R., Jarodzka, H., & van de Weijer, J. (2011). *Eye tracking: A comprehensive guide to methods and measures*. NY: Oxford University Press.

∗Hout, M. C., & Goldinger, S. D. (2011). Incidental learning speeds visual search by lowering response thresholds, not by improving efficiency: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 38*(1), 90–112.

∗Hsiao, J. H. W., & Cottrell, G. (2008). Two fixations suffice in face recognition. *Psychological Science, 19*(10), 998–1006.

∗Huestegge, L., & Koch, I. (2012). Eye movements as a gatekeeper for memorization: evidence for the persistence of attentional sets in visual memory search. *Psychological Research, 76*, 270–279.

Hyönä, J. (Ed.). (2003). Section 5: Eye movements in media applications and communication. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 607–703). Amsterdam: Elsevier Science.

∗Isaacowitz, D. M., & Choi, Y. S. (2012). Looking, feeling, and doing: Are there age differences in attention, mood, and behavioral responses to skin cancer information? *Health Psychology, 31*(5), 650–659.

Jacob, R. J., & Karn, S. K. (2003). Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 573–605). Amsterdam: Elsevier Science.

∗Jarodzka, H., Balslev, T., Holmqvist, K., Nystrom, M., Scheiter, K., Gerjets, P., & Eika, B. (2012). Conveying clinical reasoning based on visual observation via eye-movement modelling examples. *Instructional Science, 40*, 813–827.

∗Johnson, C. I., & Mayer, R. E. (2012). An eye movement analysis of the spatial contiguity effect in multimedia learning. *Journal of Experimental Psychology, 18*(2), 178–191.

∗Jones, J. L., & Kaschak, M. P. (2011). Global statistical learning in a visual search task. *Journal of Experimental Psychology: Human Perception and Performance, 38*(1), 152–160.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87*, 329–355.

∗Karacan, H., Cagiltay, K., & Tekman, H. G. (2010). Change detection in desktop virtual environments: An eye-tracking study. *Computers in Human Behavior, 26*, 1305–1313.

∗Kelly, D. J., Liu, S., Liu, S., Rodger, H., Miellet, H., Ge, H., & Caldara, R. (2011). Developing cultural differences in face processing. *Developmental Science, 14*(5), 1176–1184.

∗Kim, K., & Mundy, P. (2012). Joint attention, social-cognition, and recognition memory in adults. *Frontiers in Human Neuroscience, 6*(172), 1–11.

∗Kim, S. W., & Rehder, B. (2011). How prior knowledge affects selective attention during category learning: An eye tracking study. *Memory & Cognition, 39*, 649–665.

∗Koenig, S., & Lachnit, H. (2011). Curved saccade trajectories reveal conflicting predictions in associative learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*(5), 1164–1177.

LeCompte, M. D., & Preissle, J. (1993). *Ethnography and qualitative design in educational research*. San Diego: Academic Press.

∗Lee, F. J., & Anderson, J. R. (2001). Does learning a complex task have to be complex?: A study in learning decomposition. *Cognitive Psychology, 42*, 267–316.

Lee, B., Park, J. Y., Jung, W. H., Kim, H. S., Oh, J. S., Choi, C. H., Jan, J. H., Kang, D. H., & Kwon, J. S. (2010). White matter neuroplastic changes in long-term trained players of the game of "Baduk" (GO): A voxel-based diffusion-tensor imaging study. *NeuroImage, 52*, 9–19.

∗Lewis, M. R., & Mensink, M. C. (2012). Prereading questions and online text comprehension. *Discourse Processes, 49*(5), 367–390.

Litchfield, D., Ball, L., Donovan, T., Manning, D. J., & Crawford, T. (2010). Viewing another person's eye movements improves identification of pulmonary nodules in chest x-ray inspection. *Journal of Experimental Psychology, 16*, 251–262.

∗Liu, H. C., & Chuang, H. H. (2011). An examination of cognitive processing of multimedia information based on viewers' eye movements. *Interactive Learning Environments, 19*(5), 503–517.

∗Liu, H. C., Lai, M. L., & Chuang, H. H. (2011). Using eye-tracking technology to investigate the redundant effect of multimedia web pages on viewers' cognitive processes. *Computers in Human Behavior, 27*, 2410–2417.

∗Liu, C. J., & Shen, M. H. (2011). The influence of different representations on solving concentration problems at elementary school. *Journal of Science Education and Technology, 20*, 621–629.

Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in Cognitive Sciences, 4*(1), 6–14.

Liversedge, S., Gilchrist, I., & Everling, S. (Eds.). (2011). *The oxford handbook of eye movements.* NY: Oxford University Press.

Liversedge, S. P., Paterson, K. B., & Pickering, M. J. (1998). Eye movements and measures of reading time. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 55–75). Amsterdam: Elsevier Science Ltd.

∗Meyer, K., Rasch, T., & Schnotz, W. (2010). Effects of animation's speed of presentation on perceptual processing and learning. *Learning and Instruction, 20*, 136–145.

∗Miller, L. M., & Cassady, D. L. (2012). Making healthy food choices using nutrition facts panels: The roles of knowledge, motivation, dietary modifications goals, and age. *Appetite, 59*, 129–139.

Mintzes, J. J., Wandersee, J. H., & Novak, J. D. (1999). *Assessing science understanding.* San Diego: Academic Press.

∗Miwa, M., Egusa, Y., Saito, H., Takaku, M., Terai, H., & Kando, N. (2011). A method to capture information encountering embedded in exploratory web searches. *Information Research, 16*(3), 487.

∗Mou, W., Liu, X., & McNamara, T. P. (2009). Layout geometry in encoding and retrieval of spatial memory. *Journal of Experimental Psychology: Human Perception and Performance, 35*(1), 83–93.

∗Mu, X. (2010). Towards effective video annotation: An approach to automatically link notes with video content. *Computers & Education, 55*, 1752–1763.

∗Nakabayashi, K., Jones, T. J., Butcher, N., & Liu, C. H. (2012). Independent influences of verbalization and race on the configural and featural processing of faces: A behavioral and eye movement study. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(1), 61–77.

∗Neider, M. B., & Kramer, A. F. (2011). Older adults capitalize on contextual information to guide search. *Experimental Aging Research, 37*(5), 539–571.

∗Ooms, K., De Maeyer, P., Fack, V., Van Assche, A., & Witlox, F. (2012). Interpreting maps through the eyes of expert and novice users. *International Journal of Geographical Information Science, 26*(10), 1733–1788.

Öquist, G., Hein, A., Ygge, J., & Goldstein, M. (2004). Eye movement study of reading on a mobile device using the page and RSVP text presentation formats. In S. Brewster & M. Dunlop (Eds.), *Mobile human computer interaction – Mobile HCI 2004, LNCS 3160* (pp. 108–119). Berlin/Heidelberg, Germany: Springer.

∗Ozcelik, E., Arslan-Ari, I., & Cagiltay, K. (2010). Why does signaling enhance multimedia learning? Evidence from eye movements. *Computers in Human Behavior, 26*, 110–117.

∗Ozcelik, E., Karakus, T., Kursun, E., & Cagiltay, K. (2009). An eye-tracking study of how color coding affects multimedia learning. *Computers & Education, 53*(2), 445–453.

Phillips, D. C., & Soltis, J. F. (Eds.). (2009). *Perspectives on learning* (5th ed. NY: Teachers College Press.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*, 211–227.

∗Pradhan, A. K., Divekar, G., Masserang, K., Romoser, M., Zafian, T., Blomberg, R. D., Thomas, F. D., Reagan, I., Knodler, M., Pollatsek, A., & Fisher, D. L. (2011). The effects of focused attention training (FOCAL) on the duration of novice drivers' glances inside the vehicle. *Ergonomics, 54*(10), 917–931.

Radach, R., & Kennedy, A. (2004). Theoretical perspectives on eye movements in reading: Past controversies, current issues, and an agenda for future research. In R. Radach, A. Kennedy, & K. Rayner (Eds.), *Eye movements and information processing during reading* (pp. 3–26). New York: Psychology Press.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology, 41*, 211–236.

Rayner, K. (1998). Eye movement in reading and information processing: 20 years of research. *Psychological Bulletins, 124*(3), 372–422.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *The Quarterly Journal of Experimental Psychology, 62*(8), 1457–1506.

Rayner, K., Chace, K. H., Slattery, T. J., & Ashby, J. (2006). Eye movements as reflections of comprehension process in reading. *Scientific Studies of Reading, 10*(3), 241–255.

∗Rehder, B., Colner, R. M., & Hoffman, A. B. (2009). Feature inference learning and eye tracking. *Journal of Memory and Language, 60*, 393–419.

∗Rehder, B., & Hoffman, A. B. (2005a). Thirty-something categorization results explained: Selective attention, eyetracking, and models of category learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(5), 811–829.

∗Rehder, B., & Hoffman, A. B. (2005b). Eye tracking and selective attention in category learning. *Cognitive Psychology, 51*, 1–41.

∗Renkewitz, F., & Jahn, G. (2012). Memory indexing: A novel method for tracing memory processes in complex cognitive tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(6), 1622–1639.

∗Roderer, T., Krebs, S., Schmid, C., & Roebers, C. (2012). The role of executive control of attention and selective encoding for preschoolers' learning. *Infant and Child Development, 21*, 146–159.

∗Roderer, T., & Roebers, C. M. (2010). Explicit and implicit confidence judgments and developmental differences in meta-memory: An eye-tracking approach. *Metacognition and Learning, 5*(3), 229–250.

San Agustin, J., Skovsgaard, H., Mollenbach, E., Barret, M., Tall, M., Hansen, D. W., & Hansen, J. P. (2010). Evaluation of a low-cost open-source gaze tracker. In *Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications, Austin, Texas. (March 22 - 24).* http://dx.doi.acm.org/10.1145/1743666.1743685

∗Schmidt-Weigand, F., Kohnert, A., & Glowalla, U. (2010). A closer look at split visual attention in system- and self-paced instruction in multimedia learning. *Learning and Instruction, 20*, 100–110.

∗Schmiedtova, B. (2011). Do L2 speakers think in the L1 when speaking in the L2? *International Journal of Applied Linguistic, 8*, 138–179.

∗Schneider, E., Maruyama, M., Dehaene, S., & Sigman, M. (2012). Eye gaze reveals a fast, parallel extraction of the syntax of arithmetic formulas. *Cognition, 125*, 475–490.

Schnotz, W., Vosniadou, S., & Carretero, M. (1999). *New perspectives on conceptual change.* Oxford: Elsevier Science.

∗Sekiguchi, T. (2011). Individual differences in face memory and eye fixation patterns during face learning. *Acta Psychologica, 137*, 1–9.

∗Shatzman, K. B., & McQueen, J. M. (2006). Prosodic knowledge affects the recognition of newly acquired words. *Psychological Science, 17*(5), 372–377.

∗She, H. C., & Chen, Y. Z. (2009). The impact of multimedia effect on science learning: Evidence from eye movements. *Computers & Education, 53*, 1297–1307.

∗Smerecnik, C. M., Mesters, I., Kessels, L. T., Ruiter, R. A., de Vries, N. K., & de Vries, H. (2010). Understanding the positive effects of graphical risk information on comprehension: Measuring attention directed to written, tabular, and graphical risk information. *Risk Analysis, 30*(9), 1387–1398.

∗Stieff, M., Hegarty, M., & Deslongchamps, G. (2011). Identifying representational competence with multi-representational displays. *Cognition and Instruction, 29*(1), 123–145.

∗Tremblay, A. (2011). Learning to parse liaison-initial words: An eye-tracking study. Bilingualism: Language and. *Cognition, 14*(3), 257–279.

Tsai, M.-J., Hou, H. T., Lai, M. L., Liu, W.-Y., & Yang, F. Y. (2012). Visual attention for solving multiple-choice science problem: An eye-tracking analysis. *Computers & Education, 58*(1), 375–385.

Underwood, G., & Radach, R. (1998). Eye guidance and visual information processing: Reading, visual search, picture perception and driving. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 1–28). Oxford: Elsevier.

∗van Asselen, M., Sampaio, J., Pina, A., & Castelo-Branco, M. (2011). Object based implicit contextual learning: A study of eye movements. *Attention, Perception, & Psychophysics, 73*, 297–302.

van Gog, T., Jarodzka, H., Scheiter, K., Gerjets, P., & Paas, F. (2009). Attention guidance during example study via the model's eye movements. *Computers in Human Behavior, 25*, 785–791.

van Gog, T., & Scheiter, K. (2010). Eye tracking as a tool to study and enhance multimedia learning. *Learning and Instruction, 20*, 95–99.

∗Wang, T., & Mitchell, C. (2011). Attention and relative novelty in human perceptual learning. *Journal of Experimental Psychology: Animal Behavior Processes, 37*(4), 436–445.

∗Welham, A. K., & Wills, A. J. (2011). Unitization, similarity, and overt attention in categorization and exposure. *Memory & Cognition, 39*, 1518–1533.

∗Whitford, V., & Titone, D. (2012). Second-language experience modulates first- and second-language word frequency effects: Evidence from eye movement measures of natural paragraph reading. *Psychonomic Bulletin & Review, 19*, 73–80.

*Wiebe, E. N., Minogue, J., Jones, M. J., Cowley, J., & Krebs, D. (2009). Haptic feedback and students' learning about levers: Unravelingthe effect of simulated touch. *Computers & Education, 53*, 667–676.

*Wills, A. J., Lavric, A., Croft, G. S., & Hodgson, T. L. (2007). Predictive learning, prediction errors, and attention: Evidence from event-related potentials and eye tracking. *Journal of Cognitive Neuroscience, 19*(5), 843–854.

*Wonnacott, E., Newport, E. L., & Tanenhaus, M. K. (2008). Acquiring and processing verb argument structure: Distributional learning in a miniature language. *Cognitive Psychology, 56*, 165–209.