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Visual behavior, flow and achievement in game-based learning

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ABSTRACT

This study utilized eye-tracking technology to explore the differences between high- and low-conceptual-comprehension players' visual behaviors and game flows in game-based learning (GBL). A total of 22 university students participated in this study and their eye movements while playing a physics game were recorded by an eye tracker. Along with eye-tracking measures, the participants' prior knowledge, flow and comprehension test scores were collected. Multiple data analysis methods including MWU tests, correlation analyses, heat map analyses and lag sequential analyses were employed in this study. The results indicated that the players in the high comprehension group demonstrated an efficient text-reading strategy and better metacognitive controls of visual attention during game plays; while those in the low comprehension group could have some difficulties in decoding the conceptual representations. In addition, the players with higher comprehension expressed a higher level of game flow in two aspects: the sense of control and concentration. Furthermore, the percentages of fixation for the main task and prompt messages were associated with the players' game flow experience, especially the time distortion feeling. This study successfully applied eye-tracking technology to find learners' visual behavioral patterns in GBL environment and confirmed the flow construct for GBL, which may provide some insights for the learning mechanism of GBL. Future studies have been suggested in this paper.

1. Introduction

The rapid advances and growth in technology, computer games, particularly serious games or educational games, have demonstrated great potential for learning and instruction. According to the Federation of American Scientists (2006), computer games are especially useful in developing higher-order skills such as multi-tasking, strategic thinking, problem solving and decision making. Up to now, most Game-Based Learning (GBL) research has focused mainly on investigating its effectiveness (Cheng, Su, Huang, & Chen, 2014; Proske, Roscoe, & McNamara, 2014) in terms of its accompanying instructional

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strategies, learning achievements (Hsu, Tsai, & Wang, 2012; Ke, 2014), motivation (Huizenga, Admiraal, Akkerman, & Dam, 2009; Papastergiou, 2009), engagement (Inal & Cagiltay, 2007; Ronimus, Kujala, Tolvanen, & Lyytinen, 2014) and behavioral patterns (Hou, 2012). However, little game research has been conducted to identify players' visual behaviors and aforementioned higher-order skills through eye-tracking techniques.

Multi-tasking interaction is one of the central features of game playing and game-based learning. For example, when playing a shooting game, the players need to rapidly shift their visual attention among various types of iconic and textual information, such as types of weapon, amounts of ammunition, popping-up targets and feedback from the system. At the same time, they need to know the progress of their own performance, think of possible strategies, make decisions and take action repeatedly in just a few seconds. The coordination of all these cognitive activities requires effective and efficient control over individuals' attention resources. Research on game playing has suggested that games may improve players' multi-tasking capabilities (Chiappe, Conger, Liao, Caldwell, & Vu, 2013; Glass, Maddox, & Love, 2013; Hubert-Wallander, Green, & Bavelier, 2011). For instance, Glass et al. (2013) found that participants' cognitive flexibility was significantly improved after engaging in a strategic game in which they needed to maintain and rapidly switch their attention between multiple sources of information. Similarly, Hubert-Wallander et al. (2011) indicated that expert players outperformed novices in different aspects of visual attentional capabilities, such as attention in space, in time, and to the objects in a game. In addition, Chiappe et al. (2013) found that playing video games could enhance players' ability to carry out additional tasks, such as communication and systems monitoring, by increasing their attentional capacity.

Although multi-tasking games demand a large number of attentional resources, they can also have the potential to improve players' attentional and cognitive capabilities. The relationships between playing games and cognitive capacities can be explained by cognitive load theory (Sweller, Ayres, & Kalyuga, 2011). The basic assumption of cognitive load theory is rooted in the capacity theory of attention (Baddeley, 1992) that human working memory capacity has its inherent limits. Given that every game has its inherent complexity and difficulty which demands a certain amount of cognitive resources (i.e., the intrinsic cognitive load), if its design, such as its layouts, tools or task demands, requires an extra amount of cognitive resources for processing the information it conveys (i.e., the extraneous cognitive load), a player may suffer from cognitive overload. How the players control their cognitive resources may be the key to their achievements in game playing. It has been suggested that players' visual attention allocations among the elements in a game can reveal the metacognitive strategies for playing games by using eye-tracking measures (Chen & Tsai, 2015; Fowler & Cusack, 2014; Tsai & Pai, 2012). Therefore, eye-tracking measures may serve as an indication of effective multi-tasking learners in game-based learning.

In addition to the accomplishment in cognitive domains, playing multi-tasking games may also afford players a unique experience in the affective domains, such as flow. According to Csikszentmihalyi (1990), flow means the completely engaging state of mind when immersed in an activity. Kiili (2005b) categorized the characteristics of flow into two dimensions. One is the flow antecedent dimension including the following five factors: challenge-skill balance, clear goals, unambiguous feedback, control, and action-awareness merging. The other is the flow experience dimension which includes the four factors of concentration on the event at hand, transformation of time, autotelic experience, and loss of self-consciousness. The former means the factors that stimulate activity participants to achieve flow, while the latter indicates the participants' mental experience during the activity. Kiili (2005a) presented a framework of the Experiential Gaming Model. This model stresses the importance of providing the player with challenges that correspond with their skill level in educational games to create an appropriate environment for flow experience. It also stresses the players' repeated observation of and reflection on the game state in order to promote cognitive learning in the flow state. Recent research has also reported that game-playing engagement plays an essential role in GBL activities (Barzilai & Blau, 2014). Many game studies have identified the positive impacts of experiencing flow, such as leading learners to voluntarily engage in and repeat activities (Engeser & Rheinberg, 2008), improving game performance (Admiraal, Huizenga, Akkerman, & Dam, 2011) and motivating learners to attempt challenging tasks during game play (Kiili, 2005b; Lim, Nonis, & Hedberg, 2006) as well as the positive correlation with the adoption of learning strategies (Liu, Cheng, & Huang, 2011). These studies seem to suggest that relationships exist among flow, cognitive strategy and achievement in GBL. Hou (2015) discovered that in a GBL activity, there may be a positive relationship between players' flow level, problem solving behavioral patterns and depth of reflection. However, does flow also positively correlate with conceptual learning achievement in GBL? How do players with different levels of flow concentrate on learning in GBL? Do they pay attention to the game interfaces in the same way? To answer these questions, eye-tracking techniques provide a possible opportunity to gain more insight into them. The present study aims to analyze in depth the relationship between ‘flow antecedents’ in games, players' ‘flow experience’ while playing, students' visual attention, and learning achievements.

Eye movements are believed to be able to reflect humans' cognitive processes (Liversedge & Findlay, 2000; Rayner, 1998) and are regarded as a window onto humans' minds and brains (van Gompel, Fischer, Murray, & Hill, 2007). Eye-tracking methodology has often been used in the field of *Cognitive Science* and *Human-Computer Interaction* to examine how humans process information in reading, scene perception, human-computer interaction and media communication (Hyona, Radach, & Deubel, 2003; Rayner, 1998; Rayner, Chace, Slattery, & Ashby, 2006). Most of the prior research has focused on the basic mechanisms of human reading and visual perception with rigorous experimental controls conducted in laboratories. Fixation and saccade are the two basic characteristics of human eye movements. A fixation usually means a relatively stable state of eye movement during which the human eye's fovea is focused on the target information to be processed by the brain. A saccade refers to the rapid eye movement between any two consecutive fixations. Rooted by the eye-mind assumption (Just & Carpenter, 1980), it is believed that humans process information only when fixation occurs. That is, “cognitive factors play the dominant role in gaze control" (Henderson, Brockmole, Castelhano, & Mack, 2007, p. 557). Therefore, fixation-related measures are commonly used as indicators of human attention distribution. Saccadic data and scan paths (i.e., sequences of consecutive fixations and saccades) are used to indicate planning or cognitive strategies (Chen et al., 2014; Lai et al., 2013) or problem-solving (Grant & Spivey, 2003). Meanwhile, the greater incidence of endogenous eye blinks and larger gaze points are used to identify the areas a learner is struggling with in the game environment (Fowler & Cusack, 2014). Recently, due to the advances in technology, eye tracking has been gradually applied to educational studies as a research tool in more complex learning contexts such as multimedia learning (Canham & Hegarty, 2010; Hyona, 2010; de Koning, Tabbers, Rikers, & Paas, 2010), how color coding affects multimedia learning (Ozcelik, Karakus, Kursun, & Cagiltay, 2009), text and graphic reading (Ho, Tsai, Wang, & Tsai, 2014; Mason, Pluchino, Tornatora, & Ariasi, 2013; Mason, Tornatora, & Plichino, 2013), problem solving strategies (Hegarty, Mayer, & Monk, 1995; Lin & Lin, 2014; Susac, Bubic, Kaponja, Planinic, & Palmovic, 2014; Tsai, Hou, Lai, Liu, & Yang, 2012), and the effects of individual factors (Chen & Yang, 2014; Ho et al., 2014). In digital learning research, most of the studies have examined the effects of multimedia materials used for instruction and how learners pay attention to the designed materials. The instructional multimedia used in these studies were mainly represented in texts, static images or dynamic images such as movies (van Gog & Scheiter, 2010).

Recently, some researchers have attempted to extend the application of eye-tracking technology to explore learning in GBL environments. GBL environments are highly interactive learning environments involving the control of multi-tasking coordination over multiple dynamic representations. Tsai and Pai (2012) advocated that tracking learners' eye movements in GBL environments should be able to provide valuable insights for understanding learners' cognitive engagement during game playing as well as exploring the patterns of effective visual strategies for successful GBL. Fowler and Cusack (2014) clearly introduced how the indicators (cumulative fixation time, scan path, saccade, and eye blinks) provided from the eye-tracking device relate to the video game playing. For instance, where players look on the screen, how long they look, and how many times they look at that particular object can refer to what they are thinking about or where they are having difficulties in the game. Utilizing eye-tracking technology, Chen and Tsai (2015) successfully tracked and observed children's and adults' eye movements along with hand motions during active virtual game playing. Based on the video coding of the sequences of gaze and hand events, they found that children and adults utilized different eye-hand coordination strategies in games. They also suggested that eye-tracking analyses can be used to reveal players' control or metacognitive strategies for learning, i.e., their game-based learning strategies.

In sum, eye-tracking technologies may provide valuable insights for GBL researchers and game developers to better understand how people learn from game playing. Based on eye-tracking results, game developers can develop effective games for enhancing successful learning. However, there remains little research on players' visual attention distributions and patterns to uncover the corresponding cognitive processes (Liversedge & Findlay, 2000). Therefore, this study was conducted to fill this gap.

2. Purpose

Eye-tracking measures can, to some degree, reveal humans' cognitive learning processes, especially players' attention distributions and implicit cognitive strategies. In order to explore the patterns of visual strategies for effective GBL, this study used eye-tracking technology to track and observe players' eye movements while learning in a GBL environment. Also, this study aimed at examining the roles of flow and game achievement in conceptual learning achievement in GBL. According to the previous discussion, this study includes the following three research questions:

1. Do players with different conceptual comprehension in GBL have different visual attention distributions while playing games? If yes, what are the patterns for high and low achievement players?
2. Do players with different conceptual comprehension in GBL have different patterns of visual attention transactions (representing the players' control strategies of multi-tasking coordination applied in the game)?
3. Do players with different levels of conceptual comprehension in GBL experience different levels of game flow?

To answer these questions, all participants were divided into either the high or the low comprehension groups for conducting further comparisons. We describe how the comparisons were performed in detail later in the Method section.

3. Method

3.1. Participants

A total of 22 university students with a mean age of 21.14 years ($SD = 2.57$) volunteered to participate in the GBL task equipped with an eye-tracker to record their visual behaviors. The participants consisted of 13 males and 9 females with various majors such as design, business administration and engineering. All participants claimed that they had prior experience of playing computer games. On average, they played computer games six times a week ($SD = 4.06$) and the duration of each period of play was about 1.8 h ($SD = 1.76$).

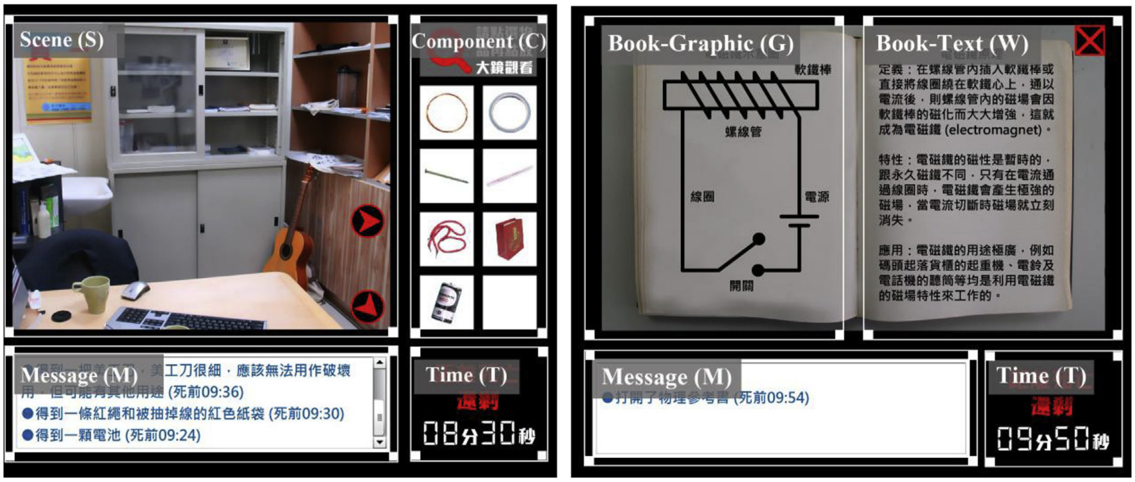
3.2. GBL task and environment

A problem-based learning task was used in the GBL environment for this study. The goal of the task was to solve a problem embedded in a game-based scenario by applying their understanding of electromagnets. The game-based learning system adopted in this study was "Escape the Lab" (Hou & Chou, 2012), a digital simulation game combining a role-play situation with problem-solving tasks for teaching electromagnets. This game was developed with FLASH CS5. Regarding the game task, in this game, a participant played the role of a female researcher who is poisoned and locked in a research room. The player must seek any clues and collect items in 10 min to make an electromagnet. With the electromagnet, the player would be able to attract the spare key under a bookshelf and escape from the room. This was an educational game integrating contextual exploration (the player actively looks for clues with guidance) and simulation manipulation (the player accurately makes an electromagnet). To solve the problem, the learners were required to perform the following behaviors in sequence within ten minutes: (1) finding the components for making an electromagnet, (2) setting up the electromagnet, (3) utilizing the electromagnet to find a lost key, and (4) using the key to unlock a door. If the learners did not have a basic understanding of electromagnets, including the major components and how to assemble them, they would not be able to solve the given problem. Time management, information selection and problem solving strategies were also important for controlling the learning process.

Two user interfaces were designed in the "Escape the Lab" game: the main interface and the reference book interface. The main interface of "Escape the Lab" was, according to its functions, divided by black frames (as shown on the left of Fig. 1) into four areas, Scene (S), Component (C), Message (M), and Time (T). The Scene area shows the exploring field of the game, where the players move around and search for the components needed to assemble the electromagnet. The upper right area is Component, where the players keep the components they collect from the Scene. The bottom left area is Message, where information about the game, such as its progress and the hints for solving the problem, are displayed. The bottom right area is Time, where the time left to finish the task is shown. In addition, to help the players learn the content knowledge of electromagnets, a reference book is provided in the Scene as a conceptual scaffold (as shown on the right of Fig. 1). Regarding the reference book interface, there are two areas in the one-page reference book. The left is a graphic area (G) illustrating a circuit figure of an electromagnet with components by graphical icons and labels, and the right is a text area (W) introducing three basic concepts of an electromagnetics in three paragraphs (definition, characteristics and applications, respectively). The content of the reference book appeared only when the player clicked on it during the play. It was designed as a scaffolding cue to help players recall their prior knowledge about the concepts of electromagnetics which were the keys to solve the problem in GBL. The students' learning process in the game is demonstrated in the following. First, the player must seek and choose relevant items in the Scene area for the possible components of an electromagnet (displayed in the Component area) or get more clues (displayed in the Message area). The player needs to find an appropriate desk in the Scene area to assemble the electromagnet. The way to assemble the electromagnet is similar to using simulation software, with the player choosing appropriate items in the Component area to assemble the electromagnet on the desk in the right order. At the end of the task, the player will get the assembled electromagnet and finally get the key to escape from the lab.

3.3. Equipment

A faceLAB 4.6 eye-tracking system with a sampling rate of 60 Hz was used to track participants' eye movements while applying their concepts of electromagnetism to play the game. This is a remote eye-tracking system which allows the



●得到一把美工刀·美工刀很細·應該無法用作破壞用·但可能有其他用途 (死前09:36)
●得到一條紅繩和被抽掉線的紅色紙袋 (死前09:30)
●得到一顆電池 (死前09:24)

定義：在螺線管內插入軟鐵棒或直接將線圈繞在軟鐵心上·通以電流後·則螺線管內的磁場會因軟鐵棒的磁化而大大增強·這就成為電磁鐵 (electromagnet)。

特性：電磁鐵的磁性是暫時的·跟永久磁鐵不同·只有在電流通過線圈時·電磁鐵會產生極強的磁場·當電流切斷時磁場就立刻消失。

應用：電磁鐵的用途極廣·例如碼頭起落貨櫃的起重機、電鈴及電話機的聽筒等均是利用電磁鐵的磁場特性來工作的。

●打開了物理參考書 (死前09:54)

Fig. 1. The main interface of the "Escape the Lab" game (left) and the reference book interface provided in the game (right).

participants’ heads to move freely during experiments. GazeTracker 8.0 was used to calculate and analyze the eye fixation data as well as output the preliminary eye-tracking measures for further statistical analyses. The MATLAB programming software was used to further calculate and visualize the eye-tracking data.

3.4. Instrument

To examine participants' prior knowledge of the learning task, a pre-test was designed to measure their basic theoretical concepts of electromagnets. It was developed by one high school physics teacher and validated by two science educators specializing in physics. A total of nine multiple-choice questions were included in the test with a total score of 90. A sample item is, “*Which of the following will make the magnetic force of an electromagnet stronger? (a) rubbing the coil; (b) changing the current direction; (c) changing the coil direction; (d) increasing the number of coils.*” The pre-test was used before the participants played the game in order to assess the group equity in prior knowledge. The post-test of the study was a comprehension test which measured participants' conceptual and procedural knowledge required for success in this GBL task after playing the game. It was designed by one of the authors and validated by two science educators specializing in physics. The post-test consisted of ten questions in which four were drawn from the pre-test conceptual questions and another six were designed based on the specific procedures or contexts required for completing the GBL task. The comprehension post-test scores served as learning achievement scores in this study. A sample item is, “*In the game you just experienced, what is the main function of the battery? (a) to supply the electronic voltage for the electromagnet; (b) to increase the weight of the electromagnet to help it fall; (c) the metal shell can be used as a magnetized peeler; (d) the above are all correct.*” The total score of the post-test was 100. The Cronbach's alphas for the pretest and the posttest were 0.54 and 0.62 respectively. They were calculated in a way that only 1 (answered correctly) or 0 (answered incorrectly) was coded for each item in the tests. In this case, the Cronbach's alpha reliability was the same as the KR20 reliability which was satisfied with a value above 0.5 for such a short test (Mangal & Mangal, 2013).

To measure the participants' flow experience while playing the game, this study used a questionnaire originally developed by Kiili (2006) and then translated into Chinese by Hou and Chou (2012). The questionnaire consists of two dimensions, flow antecedents and flow experience. The flow antecedents include challenge-skill balance, clear goals, unambiguous feedback, control, and action-awareness merging, while flow experience comprises concentration on the event at hand, transformation of time, autotelic experience, and loss of self-consciousness. This questionnaire includes a total of 22 questions. Each question was evaluated on a 5-point Likert scale ranging from “Disagree” to “Agree.” Sample items of the questionnaire are “*I was totally involved in playing the game*” and “*I felt differently about time while playing the game.*” The Cronbach's alpha values were 0.85, 0.75, and 0.84, respectively for flow antecedents, flow experience, and the overall survey items.

3.5. Procedure

A pretest-posttest eye-tracking experiment using the aforementioned GBL task was conducted for each participant in this study. After taking the 10 min prior knowledge pretest and having a 10 min eye-tracking calibration, each participant played the game individually on a desktop computer. A limited amount of time, 10 min, was set for each participant to complete the game task. During the whole playing process, each participant's visual behaviors and computer screens were tracked and recorded by the eye-tracking system. Immediately after playing the game, both the posttest and the flow questionnaire were administered to each participant to collect the comprehension test and the flow scores.

3.6. Data analysis

Mixed methodologies were used in this study to explore the visual attention and examine the flow between the participants with high and low conceptual achievement in GBL. First, according to the comprehension test scores (post-test scores), all participants were divided into two groups. The participants whose post-test scores were higher than the mean ($M = 74.68$, $SD = 1.98$) were assigned to the High comprehension group ($M = 89.00$, $SD = 7.38$, $N = 10$), and the rest were assigned to the Low comprehension group ($M = 60.83$, $SD = 12.40$, $N = 12$). The post-test scores were significantly different ($p = 0.00$) between the two groups. And, due to no significant difference ($p = 0.07$) was found in their pre-test scores (high: $M = 80.00$, $SD = 10.54$; low: $M = 66.67$, $SD = 17.75$), there was no need to exclude the pre-test scores’ effects for the post-test scores analyses. Therefore, this grouping was used for all of the following data analyses in this study. The pre-test and post-test scores were illustrated in Fig. 2.

After the grouping, a series of Mann-Whitney U tests were conducted to compare the eye-tracking metrics and flow scores of the two groups. In addition, heat maps analyses were used to illustrate the patterns of the visual attention distributions for the two groups during game plays. Lag sequential analyses of fixation sequences were used to explore the patterns of visual strategies for the two groups of learners. The detailed data analysis procedures regarding the eye-tracking metrics analyses, heat maps analyses and the fixation sequential analyses are explained below.

3.6.1. Eye-tracking metrics analyses

Before analyzing the eye-tracking data, a total of six Areas of Interest (AOIs) were defined according to the game interfaces mentioned previously (see Fig. 1): Scene (S), Component (C), Message (M), Time (T), Book-Graphic (G), and Book-Text (W). The

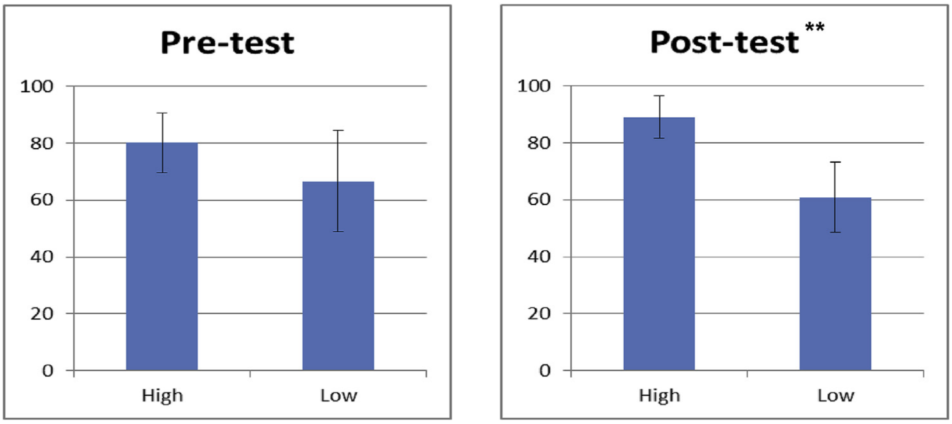


Fig. 2. The high and low comprehension groups' pre-test scores (left) and post-test scores (right). The pre-test scores were not significantly different, but the post-test scores (right) were significantly different **: $p < 0.01$.

S, C, M and T were included in the main interface; while the G and the W were belonged to the book interface. To examine how the participants paid attention to these AOIs, eye-tracking measures including *percentage of time spent in zone* (PTS), *percentage of fixation duration in zone* (PFD) and *percentage of fixation count in zone* (PFC) were output for each AOI using the GazeTracker 8.0 software. PTS refers to the percentage of time spent viewing an AOI compared with the total time spent playing. PFD refers to the percentage of time spent fixating on an AOI compared to the total fixation duration tracked while playing. PFC indicates the number of fixations allocated within an AOI compared to the number of total fixations recorded while playing. To explore visual distribution differences, all of the above metrics for all AOIs were compared between the high and the low comprehension groups.

3.6.2. Heat maps analyses

To further explore patterns and profile the details of participants' visual attention distributions in different groups, for each group, two heat maps were analyzed for the two user interfaces (the main interface and the reference book interface) designed in this study. Using a revised version of the MATLAB program developed in a prior study (Tsai et al., 2012), this study output the heat maps based on the group mean of normalized fixation duration allocated on each pixel of the screen for each interface. Group differences in visual attention distributions on the interfaces can be revealed, to some degree, by the color, the number and the locations of the red nodes (i.e., the hot zones) shown in the heat maps. Heat map analyses have gradually been supported in recent eye-tracking software and reported in recent educational studies (e.g., Tsai, et al., 2012; Ho et al., 2014; Lin & Lin, 2014).

3.6.3. Lag sequential analyses

Based on the sequences of fixated AOIs, a lag sequential analysis was used in this study to analyze the patterns of the learners' visual attention transaction during the game plays for different groups. Lag sequential analysis allows the calculation of a series of behavior transition matrices and helps us visualize participants' behavioral patterns (Bakeman & Gottman, 1997; Hou, 2012). For example, it can be used to analyze whether a sequence of a certain behavior followed by another achieved statistical significance. Sequential analysis has been gradually and widely employed in many studies on educational technology, including the eye-tracking analysis of learners' problem-solving processes (Tsai et al., 2012) and the process of game-based learning (Hou, 2012).

4. Results

To explore the effective visual attention distribution and visual strategies for conceptual learning in GBL and to examine the role played by game flows in GBL, multiple data analyses methods were used based in this study. This section presented the results of these analyses which included the MWU tests on eye-tracking measures, the heat maps analyses, the lag sequential analyses and the MWU tests on the flow scores.

4.1. Results of MWU tests on eye-tracking metrics

A series of Mann-Whitney U tests were conducted to examine the significant differences between the high and low comprehension groups for the eye-tracking measures of the six AOIs. According to Table 1, a significant difference with a large effect size (absolute $r = 0.50$) was found in the measures of the Component area, namely the percentage of fixation count in zone (PFC, $U = 30$, $Z = -1.978$, $p < 0.05$). Participants of the high comprehension group had lower PFC ($M = 10.38\%$, $SD = 4.01$)

Table 1
MWU tests on the eye-tracking measures for the AOIs of the High and Low Comprehension Groups.

AOI	Measure	Mean (*SD*)		MWU	Z	Asymp. Sig. (2-tailed)	Effect size |r|
		High	Low				
Scene	PTS	55.31(10.81)	50.94 (13.17)	47.00	−0.86	0.391	0.217
	PFD	63.63 (12.35)	62.17 (8.13)	48.00	−0.79	0.429	0.200
	PFC	60.64 (11.88)	59.35 (8.01)	54.00	−0.40	0.692	0.100
Component	PTS	8.95 (3.23)	11.90 (6.00)	42.00	−1.19	0.235	0.300
	PFD	10.95 (4.61)	16.03 (6.16)	33.00	−1.78	0.075	0.450
	PFC	10.38 (4.01)	14.70 (5.51)	30.00	−1.98	0.048*	0.500
Message	PTS	18.89 (7.15)	14.43 (4.55)	32.00	−1.85	0.065	0.467
	PFD	18.14 (7.89)	14.56 (4.06)	38.00	−1.45	0.147	0.367
	PFC	21.18 (8.54)	17.63 (4.34)	38.00	−1.45	0.147	0.367
Time	PTS	0.81 (0.40)	0.95 (0.58)	54.00	−0.40	0.692	0.100
	PFD	0.98 (0.60)	1.20 (0.60)	43.00	−1.12	0.262	0.283
	PFC	1.10 (0.66)	1.41 (0.69)	42.00	−1.19	0.235	0.300
Book-Graphic	PTS	1.07 (0.53)	1.91 (1.22)	33.00	−1.78	0.075	0.450
	PFD	0.90 (0.57)	1.85 (1.25)	31.00	−1.91	0.056	0.483
	PFC	1.05 (0.59)	2.10 (1.34)	29.00	−2.04	0.041*	0.517
Book-Text	PTS	2.57 (2.29)	2.63 (1.62)	53.00	−0.46	0.644	0.117
	PFD	2.78 (2.67)	2.60 (1.58)	57.00	−0.20	0.843	0.050
	PFC	2.98 (2.68)	3.14 (1.87)	51.00	−0.59	0.553	0.150

$^{*}p < 0.05$; PTS: Percentage of time spent in zone; PFD: Percentage of fixation duration in zone; PFC: Percentage of fixation count in zone; Effect size $|r| \geqq 0.5$ indicates a large effect, $0.3 \leqq |r| < 0.5$ indicates a medium effect, $0.1 \leqq |r| < 0.3$ indicates a small effect.

in the Component zone than those in the low comprehension group ($M = 14.7\%$, $SD = 5.51$). This suggests that the low comprehension group paid more attention to the Component area compared to the high comprehension group. This may indicate that the participants with poor comprehension achievements put more mental efforts into or had higher mental loads when processing the information in the Component area.

There were similar findings for the Book-Graphic area. A significant difference with a large effect size (absolute $r = 0.517$) was identified, namely the percentage of fixation count in zone ($U = 29$, $Z = -2.044$, $p < 0.05$). The low comprehension group had higher PFC than the high comprehension group. This could mean that the low comprehension group put more mental efforts into or had higher mental loads when reading the graphical information in the reference book in the GBL context.

4.2. *Results of heat maps analyses*

In order to further explore how the two groups distributed their visual attentions in the main interface and in the book interface, a total of four heat maps, two for each group, were analyzed in this study. Fig. 3 shows the heat maps of the main interface for the two groups. Overall, the visual attentions of both groups were distributed at similar locations in a similar way. Only a difference could be observed was that more salient hot zones (i.e., the darker red nodes) were found in the low comprehension group. These salient hot zones were allocated in the Component, Scene and Message windows. This indicated that the low comprehension group could deeply process some of the information provided in the Component, Scene and Message windows. Participants in the low comprehension group could make efforts on recognizing some components of electromagnets, assembling some components and reading some feedback messages.

Fig. 4 shows the output of the heat maps for the reference book interface. The book interface included a graphic area illustrating a circuit figure of an electromagnetic as well as a text area including three textual paragraphs which depicted the three concepts (definition, characteristics and applications) of electromagnetics respectively. Some group differences could be revealed by the color, the number and the locations of the red nodes (hot zones) shown in the heat maps. First, in the graphic area, the little tiny blue nodes showed that the high comprehension group paid little attention to the graphic information. With some yellow nodes shown in the graphic area, the low comprehension group seemed to pay more attention on the graphical icons (e.g., the battery icon) and labels (e.g., “battery,” “solenoid” and “electromagnet”) than the other group. Second, in the text area, there were more hot zones shown in the high comprehension group (3 red nodes) than in the low comprehension group (1 red node). The three hot zones were allocated in the three paragraphs, one at each, for the high comprehension group; while the only one hot zone was allocated in the first paragraph for the low comprehension group. This could imply that, in the text area, the high comprehension group deeply processed all the three concepts provided in the text; while the low comprehension group just deeply processed the first concept (definition of electromagnetics) in the text. In sum, regarding the reading of the reference book, some group differences in visual attention distributions were revealed via the heat maps analyses. The high comprehension group focused on reading all the concepts presented in the text and paid little attention to the graphic; while the low comprehension group seemed to read the reference book with a focus on the conceptual representations of physics terminologies embedded in both the graphic and the text.

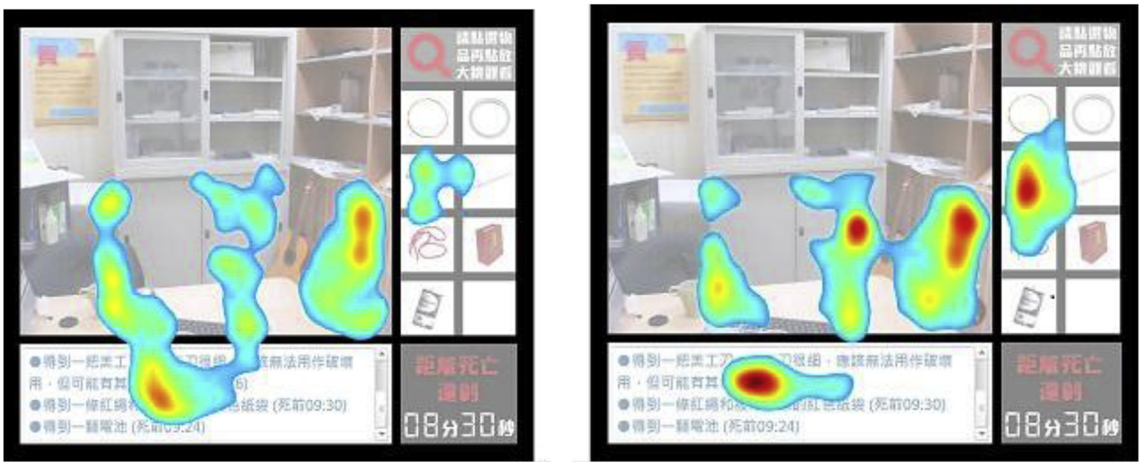


Fig. 3. Heat maps of the high comprehension group (left) and the low comprehension group (right) allocated in the main interface.

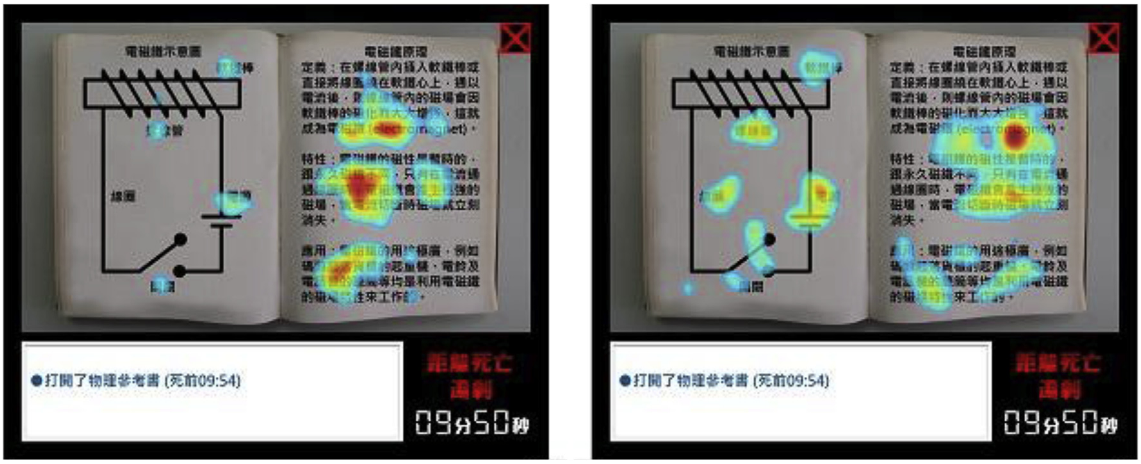

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Fig. 4. Heat maps of the high comprehension group (left) and the low comprehension group (right) allocated in the reference book interface.

4.3. Results of lag sequential analyses

To explore the patterns of visual sequences for different comprehension groups, sequential analyses were used to examine the significant fixation transactions among AOIs for each group. Tables 2 and 3 show the residual tables of z scores comparing the probabilities of actual transactions and expected transactions for each pair of AOIs within the High and the Low comprehension groups. A bold value in the tables means a significant transaction occurred from the corresponding AOI of the y-axis to the AOI of the x-axis. Using arrows to show the directions of the transactions, all of the significant transactions are

Table 2
Residual table of the high comprehension group.

	S	C	M	T	G	W	O
S	**46.46**	−25.73	−21.33	−6.52	−10.43	−19.9	−6.42
C	−20.94	**57.24**	−15.09	**4.85**	−3.20	−5.38	−2.21
M	−25.69	−9.57	**40.87**	−1.08	−4.37	−6.67	**2.14**
T	−5.53	**4.54**	−2.02	**10.82**	1.07	0.99	**4.45**
G	−10.20	−2.50	−2.28	1.07	**54.71**	**9.17**	−0.34
W	−20.31	−5.18	−7.67	1.56	**15.56**	**78.38**	−1.25
O	−4.87	−2.19	−0.02	**3.89**	0.31	−0.55	**16.20**

Note: A bold value refers to a significant transaction occurring from the corresponding AOI of the y-axis to the AOI of the x-axis. S: Scene; C: Component; M: Message; T: Time; G: Book-Graphic; W: Book-Text.

Table 3
Residual table of the low comprehension group.

	S	C	M	T	G	W	O
S	**53.07**	−32.39	−17.97	−7.58	−17.88	−22.57	−1.54
C	−28.56	**63.22**	−17.41	**7.08**	−6.32	−8.25	−1.33
M	−21.55	−12.45	**45.78**	−1.44	−5.40	−8.50	0.71
T	−5.00	**5.62**	−2.63	**15.66**	0.16	−2.46	0.03
G	−17.87	−5.60	−6.25	−0.38	**74.45**	**12.49**	0.80
W	−23.29	−7.95	−8.23	−1.19	**11.78**	**87.92**	−0.31
O	−2.90	−1.30	**2.42**	1.22	0.82	−1.09	**6.89**

Note: A bold value refers to a significant transaction occurring from the corresponding AOI of the y-axis to the AOI of the x-axis. S: Scene; C: Component; M: Message; T: Time; G: Book-Graphic; W: Book-Text.

illustrated in Fig. 5. According to Fig. 5, Tables 2 and 3, it is clear that the two groups showed some similar patterns. First, for both groups, significant recursive sequences occurred on each AOI itself, such as G→G (High: $z = 54.71$; Low: $z = 74.45$), C→C (High: $z = 57.24$; Low: $z = 63.22$), etc. In addition, for both groups, significant sequences occurred at the interaction between C and T, i.e., C→T (High: $z = 4.85$; Low: $z = 7.08$) and T→C (High: $z = 4.54$; Low: $z = 5.62$), and at the interaction between G and W, i.e., G→W (High: $z = 9.17$; Low: $z = 12.49$) and W→ G (High: $z = 15.56$; Low: $z = 11.78$). These results reveal that participants in both the high and low comprehension groups might have read each AOI repeatedly. In addition, they were concerned about the time while collecting and using the components. They might have constantly switched between the graphic and the text while reading the reference book.

However, some different patterns of fixation sequences can be observed for the two groups in Fig. 5. There were three significant sequences only shown by the high comprehension group, that is, M→O ($z = 2.14$), O→T ($z = 3.89$) and T→O ($z = 4.45$). On the other hand, there was one significant sequence only shown by the low comprehension group, i.e., O→M ($z = 2.42$). It is worth noting that the opposite direction occurred between M and O for the two groups: while the high comprehension group tended to transfer visual attention from M to O, the low comprehension group tended to transfer their attention from O to M. M refers to the messages of feedback or cueing information provided by the game system, while O indicates that the learner's visual attention was out of the screen or had escaped from the game interface. Therefore, the participants in the high comprehension group tended to escape from the game after reading the feedback messages (M→O), while the participants in the low comprehension group tended to read the feedback messages after leaving the screen (O→M). After the escape, the former group tended to check the time (O→T), and then either turned their attention away from the screen again (T→O) or went to retrieve components for the task (T→C); however, the latter group tended to continue viewing the message area (M→M) with no other linking transfer, i.e., they were trapped in the message area.

4.4. Results of the MWU tests on flow scores

Table 4 shows the flow comparison results for the high and low comprehension groups. The mean scores for most flow dimensions of learners in both the high- and the low-comprehension groups were higher than 3 (Median for a 5-point-Likert scale), and the scores of several sub-dimensions are above 4. This shows that players in this study experienced flow within 10 min when playing the game. As displayed, two significant differences were found including Control ($U = 28$, $Z = -2.180$, $p < 0.05$) and Concentration ($U = 29.5$, $Z = -2.057$, $p < 0.05$) with large effect sizes of 0.533 and 0.508 respectively. Participants of high comprehension were more likely to have a sense of control ($M = 4.40$, $SD = 0.46$) and concentration on the game task ($M = 4.65$, $SD = 0.44$) than those of low comprehension. Therefore, overall, participants with higher comprehension achievements had a higher sense of control and higher concentration in the GBL environment.

Although there was no significant difference found regarding the time distortion subscale of the flow measure between the higher and the lower achievers, significant correlations were found between the flow of time distortion and the eye-tracking measures. Based on the Spearman's correlations, we found that participants' PFC and PFD for the Scene window had significant positive correlations ($r = 0.55$, $p < 0.05$ and $r = 0.54$, $p < 0.05$, respectively) with their flow experience of time distortion. In addition, the time-distortion feeling was found to have significant but negative correlations with the eye-tracking measures for the Message window, including the PFC ($r = -0.56$, $p < 0.05$) and PFD ($r = -0.48$, $p < 0.05$). And the PFC for the Message window also had a significantly negative correlation with the overall flow experience ($r = -0.45$, $p < 0.05$) of the game play. This indicated that those participants who paid more attention to the Scene window (i.e., searching for and assembling the components for electromagnets) and paying less attention to the Message window (i.e., reading the prompted messages) tended to feel lost in time after the game. This implied that the more attention involved in the main task activity could more easily lead to a state of immersion which was characterized as being lack of the awareness of time (Jennet et al., 2008). And the prompt messages which often provided the players with feedbacks of time management actually prevented the players from feeling lost of time in the game. Furthermore, the participants who fixated more on the prompt messages seemed to have less overall flow experience during the game. In sum, the percentage of fixation could serve as an indicator of the flow experience in GBL.

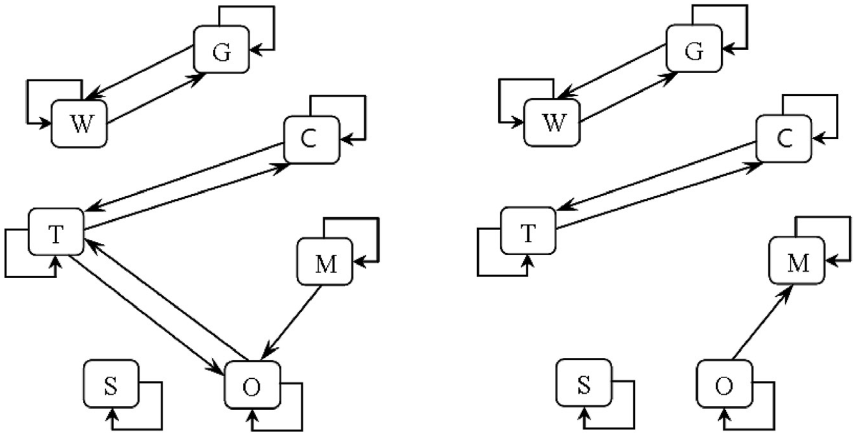

Fig. 5. Significant fixation sequences for the high comprehension group (left) and the low comprehension group (right). *Note*: S: Scene; C: Component; M: Message; T: Time; G: Book-Graphic; W: Book-Text.

Table 4
MWU tests on the flow data of the high and low comprehension groups.

	Mean (*SD*)		MWU	Z	Asymp. sig. (2-tailed)	Effect size |r|
	High	Low				
Flow Antecedents	4.02 (0.40)	3.60 (0.68)	36.50	−1.56	0.118	0.392
Challenge	3.80 (0.71)	3.63 (0.83)	55.00	-0.34	0.734	0.083
Goal	4.20 (0.79)	4.00 (0.77)	51.50	-0.57	0.567	0.142
Feedback	3.75 (0.68)	3.38 (0.71)	41.00	−1.30	0.194	0.317
Control	4.40 (0.46)	3.67 (0.83)	28.00	−2.18	0.029*	0.533
Playability	3.95 (0.64)	3.33 (0.91)	37.00	−1.57	0.117	0.383
Flow Experience	3.81 (0.63)	3.67 (0.32)	48.50	-0.76	0.446	0.192
Concentration	4.65 (0.44)	4.13 (0.51)	29.50	−2.06	0.040*	0.508
Time distortion	3.95 (1.57)	3.83 (0.69)	45.00	−1.03	0.304	0.250
Autotelic experience	4.23 (0.61)	3.69 (0.50)	32.50	−1.84	0.066	0.458
Loss of self-consciousness	2.40 (1.07)	3.04 (0.62)	34.00	−1.75	0.081	0.433

$^{*}p < 0.05$; Effect size $|r| \geqq 0.5$ indicates a large effect, $0.3 \leqq |r| < 0.5$ indicates a medium effect, $0.1 \leqq |r| < 0.3$ indicates a small effect.

5. Discussion

5.1. Visual attention distribution and conceptual comprehension in GBL

Regarding the first research question, this study analyzed players' visual attention distributions using eye-tracking measures and heat maps. For the visual distribution in the main interface, the findings show that the low comprehension group had higher percentages of fixation counts and fixation duration in Components area than the high comprehension group. In addition, from the heat maps, the colors of the hot zones were also darker in the low comprehension group, indicating more mental efforts were made by the low comprehension group. Lin and Lin (2014) reported that students tended to spend more visual attention and inspected more times on the more difficult problems. Therefore, one possible explanation is that the low comprehension group might have insufficient understanding of the components required for assembling the electromagnets. They might have encountered problems comprehending and using the components, so they had to fixate for longer and check more frequently to process the list of components. Recent research (Cheng, Lin, & She, 2015) has reported that certain game behaviors, such as viewing the relevant information embedded in the game, were significantly and positively related to game playing performances and then subsequently influenced the learning outcomes. This study further found that if the players have difficulties to decode, recognize, select or comprehend the relevant information or tools embedded in the game, they could still achieved lower in GBL.

As for the book interface which consisted of two areas (Book-Text, Book-Graphic), the eye-tracking metrics (PTS, PFD, PFC) did not have significant differences between the groups in the Book-Text area; however, in the Book-Graphic area, the PFC had a significant difference and the PFD had a marginally significant difference between the groups. This indicated that, with a higher percentage of fixations counted in the graphic area, the low comprehension group viewed the graphical information shown in the reference book more frequently than did the high comprehension group. This suggested that the low comprehension group inspected the graphical representations (the circuit figure) provided in the reference book more frequently than the high comprehension group during the game play. This might be due to the novelties or uncertainties while processing the circuit figure. According to the heat map demonstrated by the low comprehension group, it is clear that while inspecting the graphical area, this group focused on processing the conceptual icons and physics labels illustrated in the circuit figure. Therefore, the significantly reviewing behaviors of the low comprehension group might reveal their uncertainties of decoding the conceptual icons or recalling the meanings of the labels while inspecting the reference book during the game play.

Regarding the visual attention distributed in the text-area of the reference book, some group differences could be discussed based on eye-tracking metrics analyses and heat maps analyses. No significant difference was found in the group comparisons of eye-tracking metrics. This means that the two groups spent about the same time processing the overall text-area. However, the heat maps revealed that all of the three concepts were deeply processed by the high comprehension group; while only one concept was deeply processed by the low comprehension group. That is, during the similar amount of text-reading time, the high comprehension group deeply processed more concepts than the other group. This could imply that the high comprehension group had a more efficient reading strategy for the text area than the low comprehension group. The participants in the high comprehension group seemed to try to grasp all the relevant main ideas presented in the text area while reading the reference book during the play. This could support (Cheng et al., 2015)'s finding that viewing the relevant information embedded in the games could help students learn in GBL. On the other hand, the low comprehension group seemed to focus mainly on decoding the terminology in the definition section, although they paid some attention to the other two sections. They might have difficulties in recalling the term “electromagnetic” or selecting main ideas from all sections in the text. Such a problem might hinder players from gathering more clues for game playing (such as the information about the applications of electromagnetics). And, in such a case, this might result in more chances to get failures in game playing and conceptual learning.

Someone may doubt the limited affects due to the relatively small amount of reading time spent in the reference book (in average around 10–15 s spent for each of the two areas). However, the reference book was just served as a scaffolding to help players recall their prior knowledge about electromagnetics. All participants had learned the concepts about electromagnetics before. Plus the reference book contained only one page of information, i.e., an illustration and a text including around 100 characters. Therefore, such a quick visual processing for the reference book may be enough for grasping the hint to evoke relevant prior knowledge during a game play.

5.2. Visual attention transactions and conceptual comprehension in GBL

Based on the results of the lag sequential analysis, there were significant differences between the high and the low comprehension groups in the visual transactions or transfers during game play. An important finding of this study is the different visual control behaviors of the two groups after leaving the game interface. Several reasons could explain the escape from viewing the screen. The learners might just need a rest or are perhaps avoiding receiving extra external stimuli. This could save working memory resources for further processing of the perceived information, such as trying to decode feedback messages or linking the perceived information with prior knowledge retrieved from long-term memory. Kiili (2007) mentioned that when players are solving problems during game play, some of them may engage in deep reflection to repeatedly adjust their gaming strategies. In this study, if players can meaningfully construct and manage the perceived information, then they should be able to shift their visual attention back to the game interface immediately after the deep-reflection process. Otherwise, they could be lost in the game. In this study, the players with higher comprehension achievements showed clearly this metacognitive control via their visual attention transactions. They could have been aware of an increasing cognitive load while reading the feedback messages and then shifted their attention away from the screen. After gaining some understanding, the players returned their attention back to the game to first check the time, and then either evaluated the components for continuing playing the game or simply continued their thinking process. At the same time, they could have also continued to evaluate the components selected and thought about ways to assemble the electromagnet within the time limitation. This reveals a set of sophisticated metacognitive skills of time management, self-monitoring and self-regulation (Tsai, 2009) for handling the complex multi-tasking information processing required in GBL. That is, in this study, the players with better conceptual learning outcomes in GBL showed advanced learning strategies for GBL.

On the contrary, the players in the low comprehension group did not show this kind of control of visual attention, i.e., the “escaping” transaction from reading the prompted information to the process of thinking and learning. The low comprehension group only showed the significant regression to the feedback messages provided by the game. Given that the low comprehension group had lower learning performance in the posttest, they might not have fully grasped the ideas of the messages and therefore reread the message after thinking. Therefore, such a significant return or regression from outside fixations may indicate that the players had difficulties in understanding the feedback information provided in the GBL context. Although they also read the information, they may not have successfully integrated the information into the learning task. Furthermore, following the regression was a repeated loop on the message itself without any other outward transfer. This suggests that the players might have been lost in tracking the game. That is, the players with less conceptual learning showed a lack of adequate metacognitive skills or learning strategies for GBL.

5.3. Flow and conceptual comprehension in GBL

Regarding the third research question, the results indicated that players with different conceptual learning outcomes in GBL had significantly different flow experience while playing the game. Players with higher comprehension achievements self-reported a significantly higher sense of control and higher concentration than those with lower comprehension achievements. These self-reflections are consistent with the findings observed from the visual transfer behaviors shown above. For instance, after reading the messages, the high-comprehension group tended to contemplate them without paying attention to the screen. When figuring out a solution to the problem, they might check the time and then select the appropriate components needed to complete the task. This visual transfer demonstrated a certain degree of attentional control and concentration over environmental stimulus and inter-related information during the learning process. That is, better metacognitive control and concentration strategies (Tsai, 2009) revealed by selective visual attention (Sternberg, 2009) were demonstrated by the learners with better conceptual comprehension in GBL. On the contrary, the low-comprehension group tended to repeatedly read the messages without showing any specific further behaviors for solving the task, indicating a lack of metacognitive control strategies in the game-based learning environment. This finding provides evidence to support the prior studies' reports that there are significant correlations among flow, learning achievements and cognitive strategies in GBL (e.g., Liu et al., 2011; Admiraal et al., 2011; Engeser & Rheinberg, 2008; Hou & Li, 2014; Hou, 2015). That is, learners with better conceptual comprehension had higher flow of control and concentration in GBL. They showed more concentration on the main task activity and better attentional control strategies for facing the multi-tasking challenge of the game in order to avoid information overloading. Therefore, when instructors are using GBL activities, it is suggested that the instructor or the system may provide appropriate attentional guidance for students to select information more effectively so as to gain more sense of control over the activity and to focus more on the main task and finally to learn more in GBL.

In addition, in this study, we further found some significant relationships between the flow experience and visual attention involvement in GBL. The significant eye-tracking measures included PFC and PFD, which usually serve as indicators of learners' visual attention in the research of eye movement and learning (Lai et al., 2013). But the significant relationships only existed in the eye-tracking measures associated with the main task window and the message window. And the significant correlations were mainly related to the flow of time distortion in GBL. That is, the more attentional involvement was paid into the main task window during the game, the more flow experience of time distortion was reported after the game. On the contrary, the more attentional involvement was paid into the message window during the game, the less flow experience of time distortion was reported after the game. This may be due to two reasons: One was that the more involvement in the game activity could more easily lead to an immersion state which was also characterized by the lack of awareness of time (Jennet et al., 2008). The other was that the prompt messages including explicit feedbacks of time management may prevent the participants from feeling lost in time. Furthermore, for the overall flow experience, the participants who fixated more frequently on the prompt messages seemed more hardly to have the overall flow experience during the game. Therefore, the fixation frequency on the prompt messages could serve as a negative indicator of the flow experience in GBL, especially for the flow of time distortion in GBL. Future studies can further explore other possible relationships between all aspects of flow measures and eye-tracking measures in other game-based learning contexts.

Furthermore, regarding the non-significant finding in the time distortion of flow between the higher and the lower comprehension groups, it might be due to the time being limited and displayed in the user interface for both groups. A focus on time is usually required for game-based learning tasks. This is similar to Jackson and Eklund (2002) report that time distortion was a weak factor for some athletes because of the focus on time inherent in the specific activities studied (e.g., sprinting). However, in the GBL task, is the time distortion due to the time pressure (psychological factor) or due to the user interface (design factor), or to both? Based on the scanning patterns we found in this study, only the higher achievers, but not the lower achievers, demonstrated significant inter-scanning behavior between the Time zone (representing the timer) and the Out zone (representing thinking). However, they did not have significantly different levels of time distortion experience. This might imply that the display of time (i.e., the interface design) could not have a significant impact on their time distortion experience. Instead, based on the correlation analysis between flow and eye-tracking measures, the time distortion of flow was significantly related with the attention paid to the main working window and the feedback message window. This, in turn, suggests that the flow of time distortion could depend on which task they pay attention to in a multi-tasking GBL environment. However, due to the limitation of the experimental design, a confident conclusion cannot be made about this issue in this study. Further examinations concerning the impacts of user interface designs and time pressure on the time distortion of flow in GBL environments are suggested for future studies.

6. Conclusion

In order to explore the patterns of visual strategies for effective GBL, this study used eye-tracking technology to track and observe players' eye movements while learning in a GBL environment. In addition, this study also aimed at examining the roles of flow and game achievement in conceptual learning achievement in GBL. Several important findings can be summarized: First, the lower conceptual achieving players paid more visual attention to the components of the learning task, the graphic icons, the labels and the terminological definitions, suggesting that they might have had difficulties in comprehending these conceptual representations while playing. And the higher conceptual achieving players seemed to have more efficient text-reading strategies while viewing the relevant information embedded to help learning and playing. This could suggest that decoding and processing relevant information efficiently is important for GBL. Second, the players gaining more learning achievements showed a significant visual escape from the feedback messages, but were then able to return to the learning task, showing better metacognitive control of their visual attention. On the contrary, the players with less learning achievements showed problems in decoding the messages in which their attention was trapped when they returned to the game. Third, the players with better conceptual learning reported that they had experienced higher flow in terms of their sense of control and concentration while playing the game. Finally, two eye-tracking measures, the percentage of fixation count and the percentage of fixation duration, could be significant indicators for the flow experience in game-based learning, especially for the time-distortion feeling.

Briefly, this study successfully extended the application of eye-tracking technology to track learners' cognitive process in the game-based learning context, a dynamic and highly-interactive learning environment. Players' visual behaviors during game plays could be related to their conceptual learning outcomes and flow experiences in the game-based learning context. Analyses of eye-tracking metrics along with the heat maps could reveal players' reading strategies or information selection strategies in GBL. Patterns of fixation sequences may reflect learners' metacognitive control over visual attention for game-based learning. It is suggested that future studies use eye-tracking technology to further explore players’ conceptual learning and metacognitive learning strategies for different types of learning tasks in different game-based learning environments.

This study has certain limitations. First, it employed only a small sample size; a larger-sample study is recommended for future studies. Also, the lower reliabilities of the short tests used in this study could influence the group distribution and the estimate of the effect due to prior knowledge; therefore, conceptual tests with more items are suggested for future studies. In addition, we administered a pre-test to the participants to probe their prior knowledge, which might have caused some uncertain effects on their game playing and post-test scores. Therefore, future studies can design a strict experiment to examine the effects of a pre-test on game playing and on post-test scores. Also, given that game scores, or performance assessments, play an important role in game-based learning, it is suggested that a scoring system may be integrated into the game to examine the effect of game-based learning from the additional aspect. This study did not gather any qualitative feedback about how the game was experienced. As games are designed artifacts, this information can be helpful for practitioners. Moreover, the development of the game used in the present study was completed prior to our study, and it was not designed to record the log data of all the manipulated behaviors. In the future, if the game is designed to automatically record players' behaviors, we will be able to more efficiently and immediately evaluate players' learning achievements in the game and provide immediate feedback and guidance, which are helpful to players' learning and evaluation. Furthermore, we can encode more players' behaviors in the game for sequential analysis. With the behavioral sequential patterns, we can analyze players’ visual behaviors and their manipulated behaviors to have a better understanding of their learning process in the game, which would help further explore the correlation between the process and their performance in the comprehension test.

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References

Admiraal, W., Huizenga, J., Akkerman, S., & Dam, G. t (2011). The concept of flow in collaborative game-based learning. *Computers in Human Behavior, 27*, 1185–1194. http://dx.doi.org/10.1016/j.chb.2010.12.013.

Baddeley, A. D. (1992). Working memory. *Science, 255*(5044), 556–559.

Barzilai, S., & Blau, I. (2014). Scaffolding game-based learning: impact on learning achievements, perceived learning, and game experiences. *Computers & Education, 70*, 65–79. http://dx.doi.org/10.1016/j.compedu.2013.08.003.

Bakeman, R., & Gottman, J. M. (1997). *Observing interaction: An introduction to sequential analysis* (*2nd ed.*). UK: Cambridge University Press.

Canham, M., & Hegarty, M. (2010). Effects of knowledge and display design on comprehension of complex graphics. *Learning and Instruction, 20*, 155–166. http://dx.doi.org/10.1016/j.learninstruc.2009.02.014.

Cheng, M.-T., Lin, Y.-W., & She, H.-C. (2015). Learning through playing virtual age: exploring the interactions among student concept learning, gaming performance, in-game behaviors, and the use of in-game characters. *Computers & Education, 86*, 18–29. http://dx.doi.org/10.1016/j.compedu.2015.03.007.

Cheng, M. T., Su, T., Huang, W. Y., & Chen, J. H. (2014). An educational game for learning human immunology: what do students learn and how do they perceive? *British Journal of Educational Technology, 45*, 820–833. http://dx.doi.org/10.1111/bjet.12098.

Chen, S.-C., She, H.-C., Chuang, M.-H., Wu, J.-Y., Tsai, J.-L., & Jung, T.-P. (2014). Eye movements predict students' computer-based assessment performance of physics concepts in different presentation modalities. *Computers & Education, 74*, 61–72. http://dx.doi.org/10.1016/j.compedu.2013.12.012.

Chen, Y., & Tsai, M.-J. (2015). Eye-hand coordination strategies during active video game playing: an eye-tracking study. *Computers in Human Behavior, 51*, 8–14. http://dx.doi.org/10.1016/j.chb.2015.04.045.

Chen, Y. C., & Yang, F. Y. (2014). Probing the relationship between process of spatial problems solving and science learning: an eye tracking approach. *International Journal of Science and Mathematics Education, 12*, 579–603. http://dx.doi.org/10.1007/s10763-013-9504-y.

Chiappe, D., Conger, M., Liao, J., Caldwell, J. L., & Vu, K.-P. L. (2013). Improving multi-tasking ability through action videogames. *Applied Ergonomics, 44*, 278–284. http://dx.doi.org/10.1016/j.apergo.2012.08.002.

Csikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience*. New York: Harper Collins.

Engeser, S., & Rheinberg, F. (2008). Flow, performance and moderators of challenge-skill balance. *Motivation and Emotion, 32*(3), 158–172. http://dx.doi.org/10.1007/s11031-008-9102-4.

Federation of American Scientists. (2006). *Harnessing the power of video games for learning*. Retrieved 15 August, 2015, from http://informalscience.org/images/research/Summit_on_Educational_Games.pdf.

Fowler, A., & Cusack, B. (2014). A proposed method for measuring learning in video games. *GSTF Journal on Computing, 3*(4), 42–47. http://dx.doi.org/10.5176/2251-3043_3.4.288.

Glass, B. D., Maddox, W. T., & Love, B. C. (2013). Real-time strategy game training: emergence of a cognitive flexibility trait. *PLoS ONE, 8*(8). http://dx.doi.org/10.1371/journal.pone.0070350.

van Gog, T., & Scheiter, K. (2010). Eye tracking as a tool to study and enhance multimedia learning. *Learning and Instruction, 20*, 95–99. http://dx.doi.org/10.1016/j.learninstruc.2009.02.009.

Grant, E. R., & Spivey, M. J. (2003). Eye movements and problem solving guiding attention guides thought. *Psychological Science, 14*, 462–466. http://dx.doi.org/10.1111/1467-9280.02454.

Hegarty, M., Mayer, R. E., & Monk, C. (1995). Comprehension of arithmetic word problems: a comparison of successful and unsuccessful problem solvers. *Journal of Educational Psychology, 87*, 18–32. http://dx.doi.org/10.1037/0022-0663.87.1.18.

Henderson, J. M., Brockmole, J. R., Castelhano, M. S., & Mack, M. (2007). Visual saliency does not account for eye movements during visual search in real-world scenes. In R. P. G. van Gompel, M. H. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye movements: A window on mind and brain* (pp. 537–562). Amsterdam, the Netherlands: Elsevier.

Ho, H. N. J., Tsai, M.-J., Wang, C.-Y., & Tsai, C.-C. (2014). Prior knowledge and online inquiry-based science reading: evidence from eye tracking. *International Journal of Science and Mathematics Education, 12*, 525–554. http://dx.doi.org/10.1007/s10763-013-9489-6.

Hou, H.-T. (2012). Exploring the behavioral patterns of learners in an educational massively multiple online role-playing game (MMORPG). *Computers & Education, 58*, 1225–1233. http://dx.doi.org/10.1016/j.compedu.2011.11.015.

Hou, H.-T. (2015). Integrating cluster and sequential analysis to explore learners' flow and behavioral patterns in a simulation game with situated-learning context for science courses: a video-based process exploration. *Computers in Human Behavior, 48*, 424–435. http://dx.doi.org/10.1016/j.chb.2015.02.010.

Hou, H. T., & Chou, Y. S. (2012). Exploring the technology acceptance and flow state of a chamber escape game-escape the lab© for learning electromagnet concept. In *The 20th International Conference on computers in education (ICCE2012), Singapore, November 26-30, 2012*.

Hou, H. T., & Li, M. C. (2014). Evaluating multiple aspects of a digital educational problem-solving-based adventure game. *Computers in Human Behavior, 30*, 29–38. http://dx.doi.org/10.1016/j.chb.2013.07.052.

Hsu, C.-Y., Tsai, C.-C., & Wang, H.-Y. (2012). Facilitating third graders' acquisition of scientific concepts through digital game-based learning: the effects of self-explanation principles. *The Asia-Pacific Education Researcher, 21*(1), 71–82.

Hubert-Wallander, B., Green, C. S., & Bavelier, D. (2011). Stretching the limits of visual attention: the case of action video games. *Wiley Interdisciplinary Reviews: Cognitive Science, 2*, 222–230. http://dx.doi.org/10.1002/wcs.116.

Huizenga, J., Admiraal, W., Akkerman, S., & Dam, G. t (2009). Mobile game-based learning in secondary education: engagement, motivation and learning in a mobile city game. *Journal of Computer Assisted Learning, 25*, 332–344. http://dx.doi.org/10.1111/j.1365-2729.2009.00316.x.

Hyona, J. (2010). The use of eye movements in the study of multimedia learning. *Learning and Instruction, 20*, 172–176. http://dx.doi.org/10.1016/j.learninstruc.2009.02.013.

Hyona, J., Radach, R., & Deubel, H. (2003). *The mind's eye: Cognitive and applied aspects of eye movement research*. Amsterdam, The Netherlands: Elsevier Science BV.

Inal, Y., & Cagiltay, K. (2007). Flow experiences of children in an interactive social game environment. *British Journal of Educational Technology, 38*, 455–464. http://dx.doi.org/10.1111/j.1467-8535.2007.00709.x.

Jackson, A. S., & Eklund, C. R. (2002). Assessing flow in physical activity: the flow state scale-2 and dispositional flow scale-2. *Journal of Sport & Exercise Psychology, 24*, 133–150.

Jennet, C., Cox, A. L., Cairns, P., Dhoparee, S., Epps, A., Tijs, T., et al. (2008). Measuring and defining the experience of immersion in games. *International Journal of Human–Computer Studies, 66*, 641–661.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: from eye fixations to comprehension. *Psychological Review, 87*, 329–354. http://dx.doi.org/10.1037/0033-295X.87.4.329.

Ke, F. (2014). An implementation of design-based learning through creating educational computer games: a case study on mathematics learning during design and computing. *Computers & Education, 73*, 26–39. http://dx.doi.org/10.1016/j.compedu.2013.12.010.

Kiili, K. (2005a). Digital game-based learning: towards an experiential gaming model. *The Internet and Higher Education, 8*, 13–24. http://dx.doi.org/10.1016/j.iheduc.2004.12.001.

Kiili, K. (2005b). Content creation challenges and flow experience in educational games: the IT-Emperor case. *The Internet and Higher Education, 8*, 183–198.

Kiili, K. (2006). Evaluations of an experiential gaming model. *An Interdisciplinary Journal on Humans in ICT Environments, 2*(2), 187–201.

Kiili, K. (2007). Foundation for problem-based gaming. *British Journal of Educational Technology, 38*, 394–404. http://dx.doi.org/10.1111/j.1467-8535.2007.00704.x.

de Koning, B. B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2010). Attention guidance in learning from a complex animation: seeing is understanding? *Learning and Instruction, 20*, 111–122. http://dx.doi.org/10.1016/j.learninstruc.2009.02.010.

Lai, M. L., Tsai, M.-J., Yang, F.-Y., Hsu, C.-Y., Liu, T. C., Lee, S. W. Y., … Tsai, C.-C. (2013). A review of using eye-tracking technology in exploring learning from 2000 to 2012. *Educational Research Review, 10*, 90–115. http://dx.doi.org/10.1016/j.edurev.2013.10.001.

Lim, C. P., Nonis, D., & Hedberg, J. (2006). Gaming in a 3D multiuser virtual environment: engaging students in science lessons. *British Journal of Educational Technology, 37*, 211–231. http://dx.doi.org/10.1111/j.1467-8535.2006.00531.x.

Lin, J. J. H., & Lin, S. S. J. (2014). Cognitive load for configuration comprehension in computer-supported geometry problem solving: an eye movement perspective. *International Journal of Science and Mathematics Education, 12*, 605–627. http://dx.doi.org/10.1007/s10763-013-9479-8.

Liu, C.-C., Cheng, Y.-B., & Huang, C.-W. (2011). The effect of simulation games on the learning of computational problem solving. *Computers & Education, 57*, 1907–1918. http://dx.doi.org/10.1016/j.compedu.2011.04.002.

Liversedge, S. P., & Findlay, J. M. (2000). Eye movements reflect cognitive processes. *Trends in Cognitive Sciences, 4*, 6–14.

Mangal, S. K., & Mangal, S. (2013). *Research methodology in behavioural sciences*. Delhi: PHI Pvt. Ltd.

Mason, L., Pluchino, P., Tornatora, M. C., & Ariasi, N. (2013a). An eye-tracking study of learning from science text with concrete and abstract illustrations. *Journal of Experimental Education, 81*, 356–384. http://dx.doi.org/10.1080/00220973.2012.727885.

Mason, L., Tornatora, M. C., & Pluchino, P. (2013b). Do fourth graders integrate text and picture in processing and learning from an illustrated science text? evidence from eye-movement patterns. *Computers & Education, 60*, 95–109. http://dx.doi.org/10.1016/j.compedu.2012.07.011.

Ozcelik, E., Karakus, T., Kursun, E., & Cagiltay, K. (2009). An eye-tracking study of how color coding affects multimedia learning. *Computers & Education, 53*, 445–453. http://dx.doi.org/10.1016/j.compedu.2009.03.002.

Papastergiou, M. (2009). Exploring the potential of computer and video games for health and physical education: a literature review. *Computers & Education, 53*, 603–622. http://dx.doi.org/10.1016/j.compedu.2009.04.001.

Proske, A., Roscoe, R. D., & McNamara, D. S. (2014). Game-based practice versus traditional practice in computer-based writing strategy training: effects on motivation and achievement. *Educational Technology Research and Development, 62*, 481–505. http://dx.doi.org/10.1007/s11423-014-9349-2.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372–422. http://dx.doi.org/10.1037/0033-2909.124.3.372.

Rayner, K., Chace, K. H., Slattery, T. J., & Ashby, J. (2006). Eye movements as reflections of comprehension processes in reading. *Scientific Studies of Reading, 10*, 241–255. http://dx.doi.org/10.1207/s1532799xssr1003_3.

Ronimus, M., Kujala, J., Tolvanen, A., & Lyytinen, H. (2014). Children's engagement during digital game-based learning of reading: the effects of time, rewards, and challenge. *Computers & Education, 71*, 237–246. http://dx.doi.org/10.1016/j.compedu.2013.10.008.

Sternberg, R. J. (2009). *Cognitive psychology*. Belmont, CA: Wadsworth.

Susac, A., Bubic, A., Kaponja, J., Planinic, M., & Palmovic, M. (2014). Eye movements reveal students' strategies in simple equation solving. *International Journal of Science and Mathematics Education, 12*, 555–577. http://dx.doi.org/10.1007/s10763-014-9514-4.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. New York: Springer.

Tsai, M.-J. (2009). The model of strategic e-learning: understanding and evaluating students' e-learning from metacognitive perspectives. *Educational Technology & Society, 12*(1), 34–48.

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*, 375–385. http://dx.doi.org/10.1016/j.compedu.2011.07.012.

Tsai, M.-J., & Pai, H.-T. (2012). Exploring students' cognitive process in game-based learning environment by eye tracking. In *Paper presented at the 2012 world congress in computer science, computer engineering, and applied computing (WORLDCOMP'12), Las Vegas, Nevada, USA, July 16-19, 2012*.

Van Gompel, R. P. G., Fischer, M. H., Murray, W. S., & Hill, R. L. (2007). In *Eye movements: a window on mind and brain*. Oxford: Elsevier.